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SCOUR PROTECTION FOR LOCKS AND DAMS 2-10, UPPER MISSISSIPPI RIVER

Hydraulic Model Investigation

by

Jerry V. Markussen, Steven C. Wilhelms

Hydraulics Laboratory

AD-A181 889

DEPARTMENT OF THE ARMY
Waterways Experiment Station, Corps of Engineers
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<p>A 1:70-scale physical model of a typical spillway section of the locks and dams on the Upper Mississippi River was used to determine the probable cause of the scour that has occurred at these projects. It was determined that single-gate operation on the spillways created hydraulic conditions conducive to scour. A 1:42-scale model was used to develop suitable riprap protection. Two gradations of fill material were found suitable and two gradations of riprap were adequate for protection downstream of the tainter gates and roller gates at these structures. The geometric layout of the riprap depended upon the slope of the scour hole to be repaired. Lock and Dam 2 was studied separately because of its unique stilling basin configuration and operation schedule. Riprap protection similar to the other projects was devised for Lock and Dam 2.</p>					
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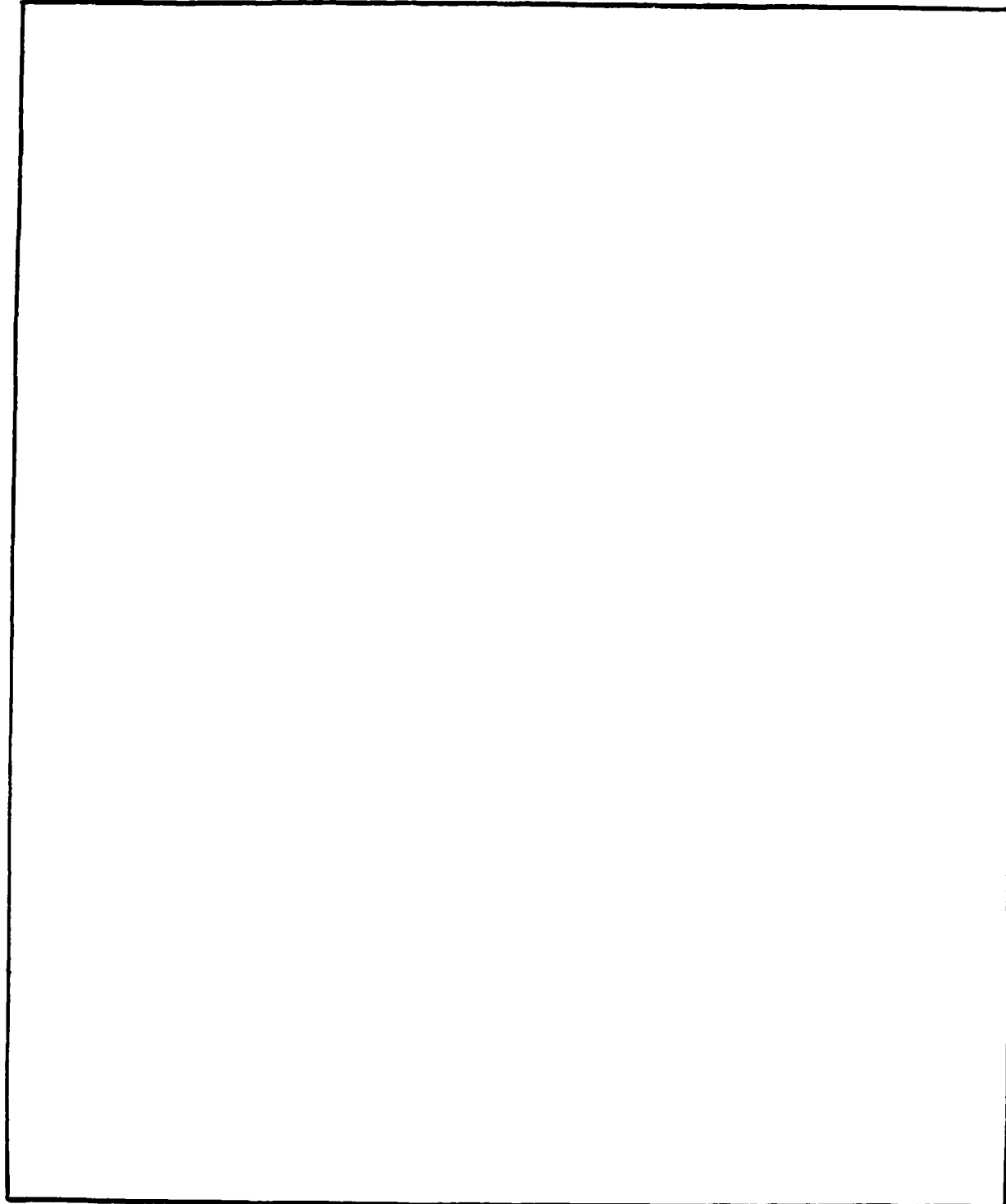
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PREFACE

The model studies reported herein were conducted at the US Army Engineer Waterways Experiment Station (WES) in the Hydraulics Laboratory (HL) during the triennium from April 1981 to September 1984. The investigation was authorized and funded by the US Army Engineer District, St. Paul (NCS). Messrs. Tom McAloon, Greg Eggers, and Jim Murphy of NCS provided guidance and insightful comments throughout the study. Messrs. Henry B. Simmons, former Chief, HL, Frank A. Herrmann, Jr., Chief, HL, and John L. Grace, Jr., Chief, Hydraulic Structures Division, directed the effort. Mr. N. Randy Oswalt, Chief, Spillways and Channels Branch (SCB), provided immediate supervision. Mr. Jerry V. Markussen, SCB, conducted the studies and analyzed the results. Mr. Steven C. Wilhelms, Reservoir Water Quality Branch, prepared this text. This report was edited by Ms. Jamie W. Leach of the Information Products Division, Information Technology Laboratory.

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CONVERSION FACTORS, NON-SI TO SI (METRIC) UNITS OF MEASUREMENT

Non-SI units of measurement used in this report can be converted to SI (metric) units as follows:

<u>Multiply</u>	<u>By</u>	<u>To Obtain</u>
cubic feet	0.02831685	cubic metres
feet	0.3048	metres
inches	2.54	centimetres
miles (US statute)	1.609347	kilometres
pounds (mass)	0.4535924	kilograms

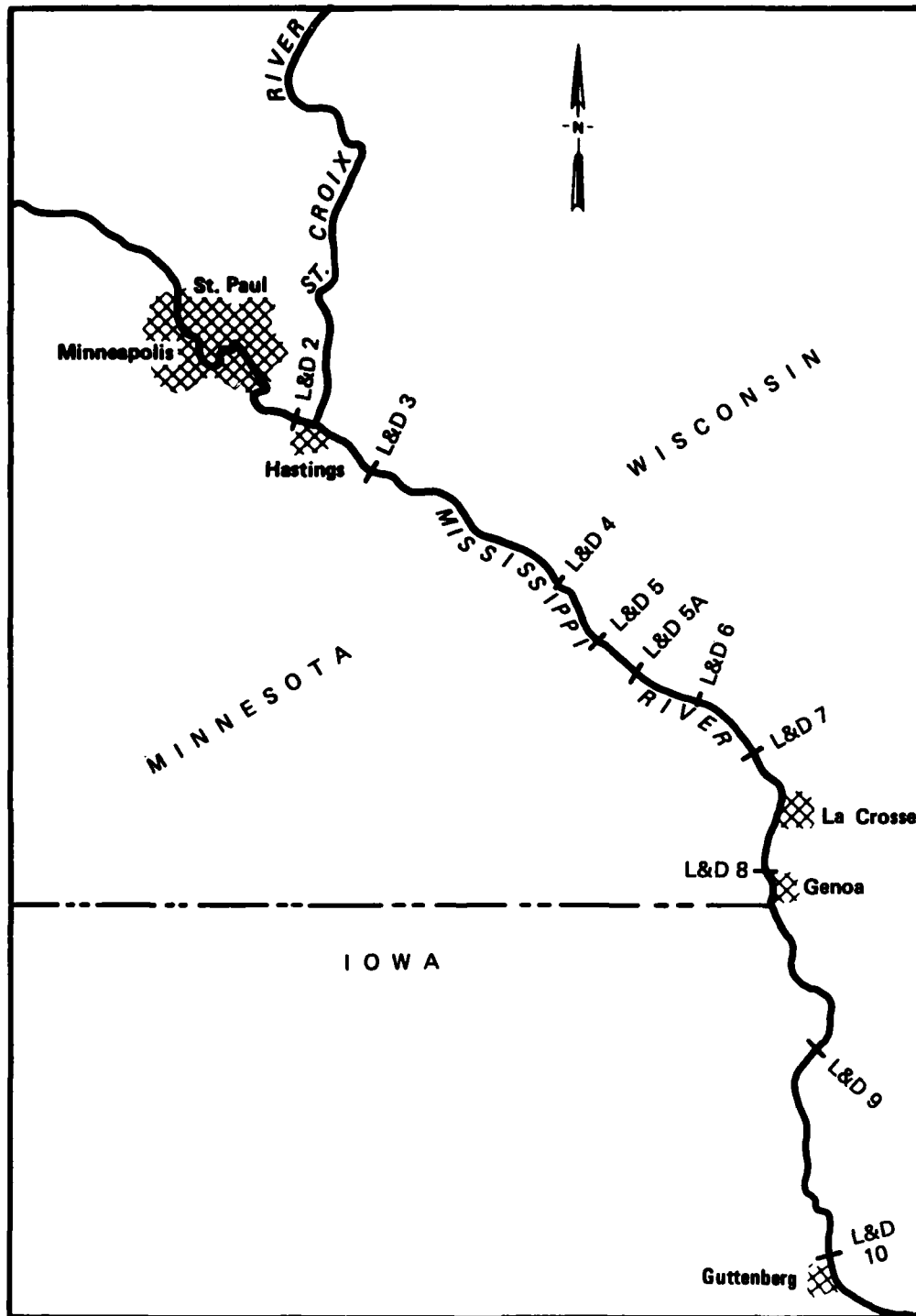


Figure 1. General locations of Locks and Dams 2-10, Upper Mississippi River

SCOUR PROTECTION FOR LOCKS AND DAMS 2-10,
UPPER MISSISSIPPI RIVER
Hydraulic Model Investigation

PART I: INTRODUCTION

Background

1. The projects under investigation in this study are located on the Upper Mississippi River from Guttenberg, Iowa (river mile 615.1,* Lock and Dam 10) to Hastings, Minn. (river mile 815.2, Lock and Dam 2) (Figure 1). These projects were opened during the 1930's to provide flood control and navigation for the Upper Mississippi River. Each project consists of a lock (sometimes a pair of locks) and a spillway section. Flow control in the spillway section is achieved with tainter gates or roller gates, or both. Normal pool differentials range from 5.5 ft to 12.2 ft for these structures.

2. Since 1952, hydrographic surveys generally have indicated that scour has occurred or is occurring upstream and downstream of these structures. Scour depths of up to 55 ft have occurred at some projects. Figure 2 shows results of these surveys at Lock and Dam 8. Similar degradation, although not as severe, was observed at the other projects. The potential for this erosion to threaten the integrity of the spillway section dictated that protective measures be taken. However, the question immediately arises: "What conditions caused the scour, and, therefore, what conditions are to be protected against?"

Purpose and Scope

3. The purpose of the studies reported herein was to determine the cause of the scour at Locks and Dams 2-10 and, subsequently, to develop a rip-rap design that would stabilize the existing conditions, thereby preventing further degradation.

* A table of factors for converting non-SI units of measurement to SI (metric) units is presented on page 3.

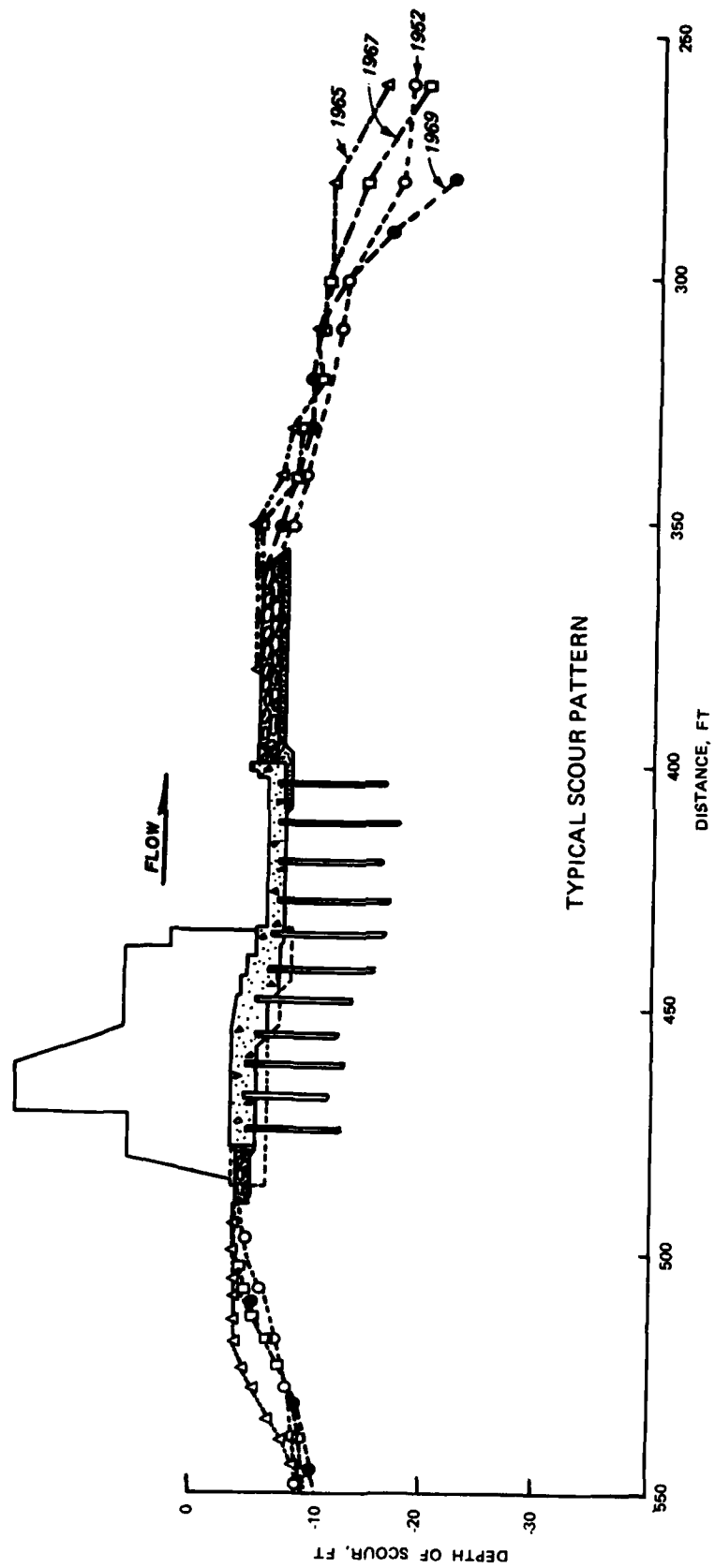


Figure 2. Hydrographic surveys upstream and downstream of Lock and Dam 8 showing scour

4. To accomplish these tasks, three types of physical models were used: (a) section models of the spillway gates, (b) three-dimensional models of several gates, and (c) a full-structure-width model. For cost effectiveness in the total modeling effort, a project site was selected that would yield information that would be applicable to several projects. At the suggestion of St. Paul District personnel, Lock and Dam 8 was selected. For design of riprap protection, similarities among all the locks and dams permitted use of a "generic" model to develop riprap protection. Lock and Dam 2 was modeled separately because of its unique stilling basin and tailrace geometry.

Prototype Description

Lock and Dam 8

5. Lock and Dam 8 is located on the Mississippi River near Genoa, Wis., at river mile 679.2 (Figure 1). The structure began operations for flood control and navigation in 1937. Design discharge for the spillway and stilling basin were based on the flood of 1880, which was estimated at 193,000 cfs. At normal pool and tailwater elevations, the head differential from upper to lower pool is 10.6 ft. At normal pool and minimum tailwater, the head differential is 15.0 ft. The project consists of a spillway section with five 80-ft-wide roller gates and ten 35-ft-wide tainter gates, a 600- by 110-ft lock, and a 15,720-ft-long earthen dike. Figure 3 shows plan and section views of the Lock and Dam 8 structure.

6. As standard operating procedure (SOP), flows up to 23,000 cfs are regulated through Lock and Dam 8 to maintain an upper pool elevation of 631.0* near LaCrosse, Wis. (Figure 1). For flows greater than 23,000 cfs but less than 95,000 cfs, discharge is regulated to maintain the upper pool elevation at the dam at el 630.0. For river discharges greater than 95,000 cfs, all the control gates are raised clear of the water allowing open river (uncontrolled) flow conditions to prevail.

7. For winter operation, the SOP changes because of icing conditions on the Upper Mississippi. Prior to icing conditions, the tainter gates are lowered into the submerged position, which eliminates most of the problems caused

* All elevations (el) cited herein are in feet referred to the National Geodetic Vertical Datum (NGVD).

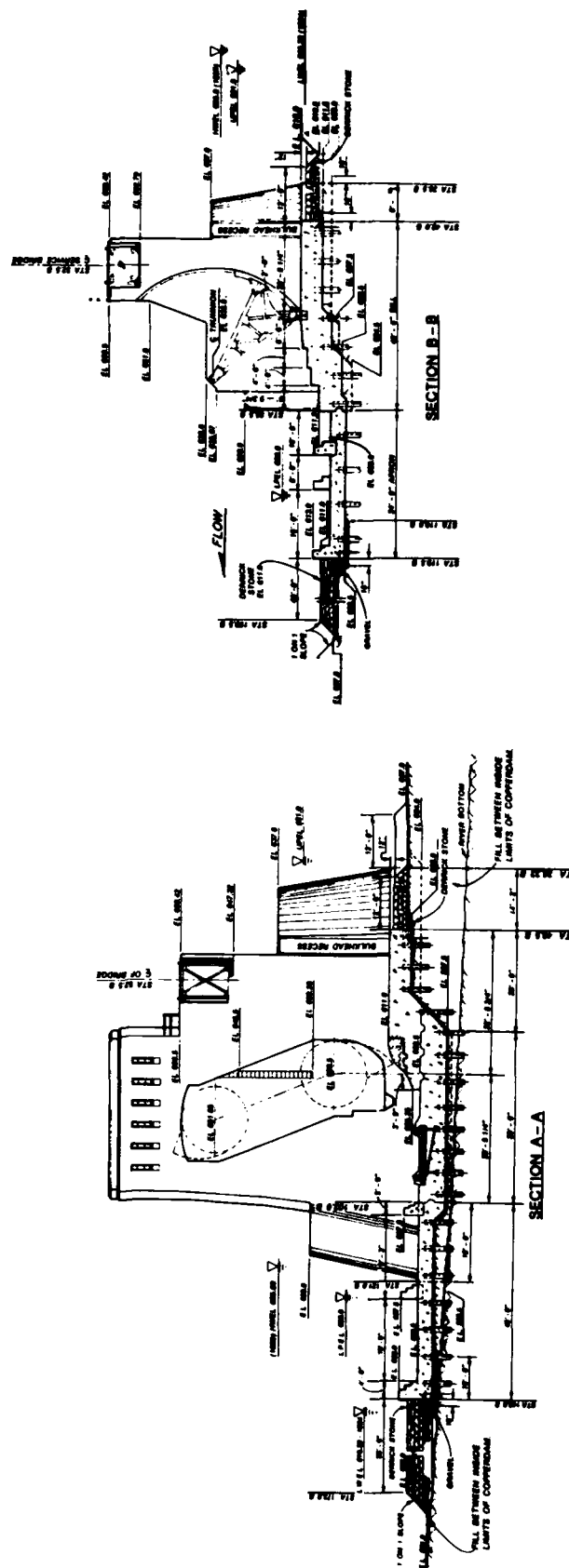
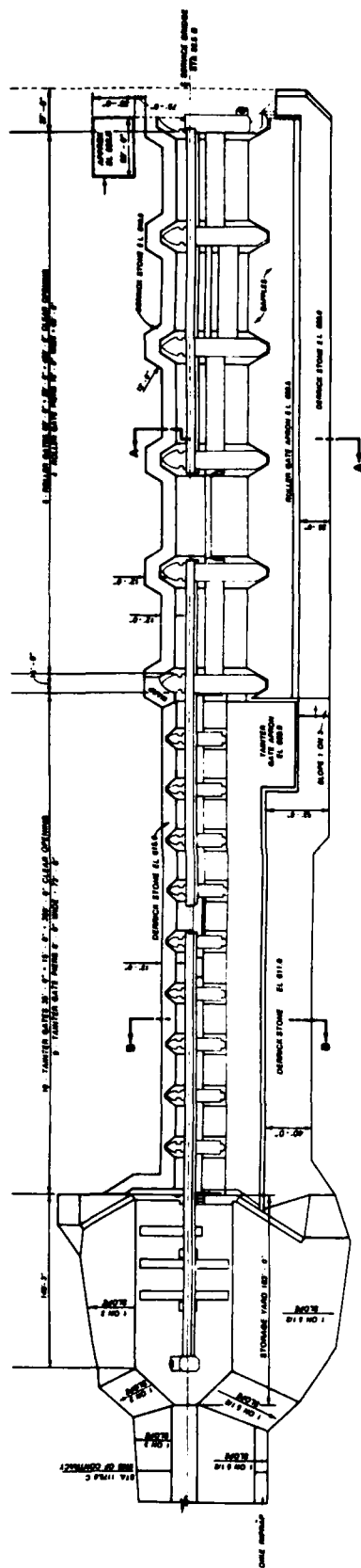


Figure 3. Plan and section views of Lock and Dam 8 structure

by ice. These gates, set to release the estimated winter base flow, subsequently freeze in that position. The upstream pool is maintained by regulating the remaining discharge with the roller gates. Ideally, the discharge is distributed evenly over the length of the five roller gates.

8. Hydrographic surveys of the tailrace and forebay areas indicate that scour action has progressively eroded the streambed upstream and downstream of the structure. Figure 4 shows a plot of the 1979 hydrographic survey of scour downstream of spillway gate 5. The scour experienced at Lock and Dam 8 is typical of that at the other Upper Mississippi River projects. The magnitude of this erosion precluded complete repair of the scour hole (i.e., restoration to postproject, 1937 conditions). Therefore, as stated earlier, the objective of these studies was to develop a riprap design that would stabilize existing conditions and protect against further degradation.

Lock and Dam 2

9. Lock and Dam 2 is located near Hastings, Minn., at Mississippi river mile 815.2 (Figure 1). The lock and dam began operation in 1931, and in 1948 a second lock was placed in operation. Design discharge for this project was 106,000 cfs. Normal upstream and downstream pool elevations for Lock and Dam 2 are 687.2 and 675.0 ft, respectively. A 600-ft-long by 110-ft-wide lock, a spillway section consisting of twenty 30-ft-wide tainter gates and a 100-ft-wide ungated concrete spillway crest, and a 3,000-ft-long earthen embankment make up the project (Figure 5).

10. Lock and Dam 2 was studied separately from the other projects because of its unique stilling basin configuration and its unusual operating procedure. A concrete stilling basin is located downstream of tainter gates 1-4 and 8-11. Downstream of gates 1-4 the basin is 80 ft long with a 5-ft-high end sill. Two rows of baffle blocks provide additional energy dissipation. A 100-ft-long stilling basin with baffle blocks is located downstream of gates 8-11. Downstream of the remainder of the tainter gates and the concrete spillway are stone-filled timber "cribs" for energy dissipation. Riprap provides bottom protection just downstream of the timber cribs.

11. The upstream pool elevation at Lock and Dam 2 is controlled by tainter gate releases until the total discharge exceeds 12,000 cfs. For discharges up to 30,000 cfs, only those tainter gates with a concrete stilling basin are operated. At 40,000 cfs, all the gates are operated for flow control. At 61,000 cfs the tainter gates are raised completely out of the water,

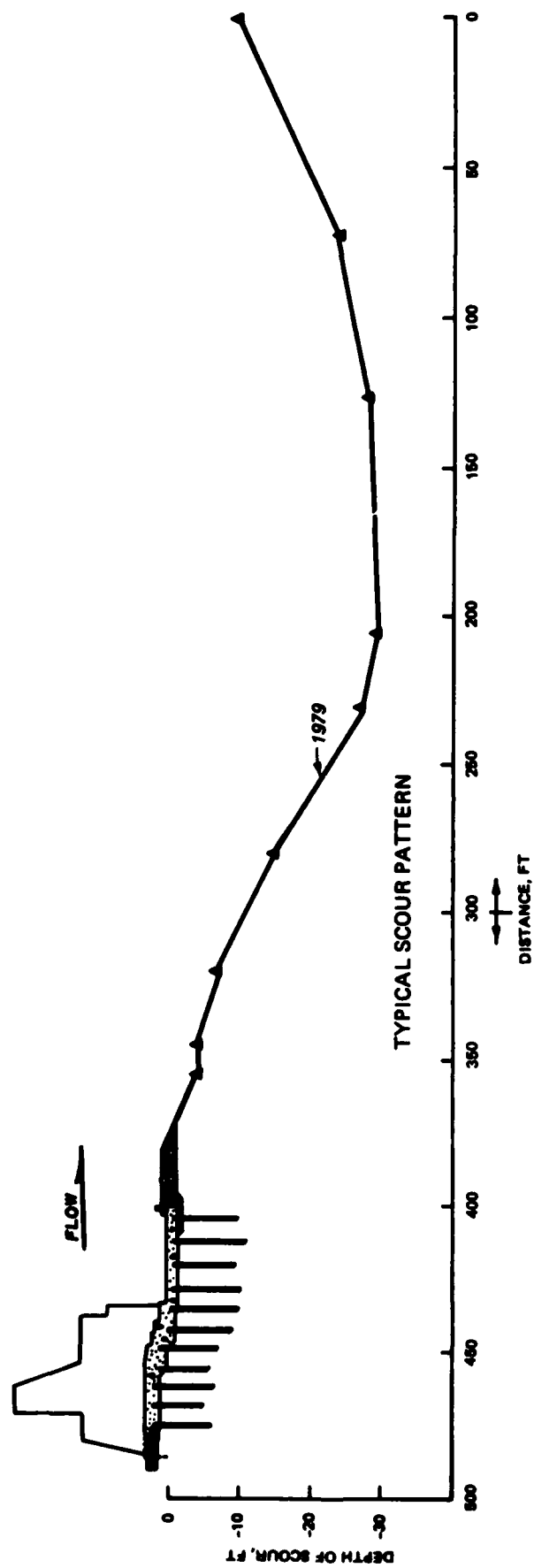


Figure 4. Results of 1979 hydrographic survey at Lock and Dam 8, gate 5, showing depth of scour

resulting in open river flow conditions at the structure.

12. For nonflood flow operation under normal conditions, the tainter gate openings are limited to prevent scour. Ordinarily, gate openings are limited so that velocity over the riprap just below the timber cribs is less than 4.5 ft/sec. In an emergency, the velocity criteria may be increased to 6.0 ft/sec.

13. For winter operation, total flow must pass through the tainter gates. Four tainter gates (two upstream of each of the concrete stilling basins) are housed by heated enclosures to prevent freezing. Flow regulation for pool maintenance is achieved with these four gates.

PART II: MODELS AND TESTING PROCEDURE

Modeling Theory

14. For accurate simulation of prototype events, relationships between model and prototype units and dimensions must be developed. Dimensional analysis indicates that the dominant forces in a free-surface hydraulic flow situation are inertial and gravitational forces. Similitude requires that the relationship of these forces in the prototype be reproduced in the model.

15. The Froude number

$$F = \frac{V}{\sqrt{gd}} \quad (1)$$

where

F = Froude number, dimensionless

V = velocity, ft/sec

g = gravitational acceleration, ft/sec²

d = characteristic hydraulic length, ft

is a dimensionless ratio of these forces. Thus, similarity between model and prototype is maintained if the Froude number of flow in the model is equal to the Froude number of flow in the prototype. This condition is achieved by equating model and prototype Froude numbers and solving for the prototype-to-model scale relationships for dimensions and hydraulic quantities of concern. Using these relationships to transfer model data to prototype equivalents ensures similarity.

16. The following ratios for scaling model quantities to prototype dimensions were used for the models discussed in this report:

<u>Dimension</u>	<u>Scale Ratio</u>	<u>Scale Relation</u>	
Length	$L_r = L_m/L_p^*$	1:70	1:42
Time	$t_r = t_m/t_p = L_r^{1/2}$	1:8.37	1:6.48
Velocity	$V_r = V_m/V_p = L_r^{1/2}$	1:8.37	1:6.48
Discharge	$Q_r = Q_m/Q_p = L_r^{5/2}$	1:40,996	1:11,432
Weight	$W_r = L_r^3$	1:343,000	1:74,088

* L_m , L_p = Length in the model and length in the prototype, respectively.

Using these scaling relationships, values for discharge, velocity, and distance may be transferred between model and prototype. Thus, a velocity in the 1:42-scale model of 1 ft/sec transfers to a prototype velocity of 6.48 ft/sec.

17. In all of the models used in this study, water was supplied from a recirculating system. Model flow rates were measured using a venturi meter. Steel rails of known elevation (relative to the model structure) were located on each side of the model flume, thereby permitting accurate measurement of scour depths and water surface elevations with a mechanical point gage.

Section Models

1:70-scale model

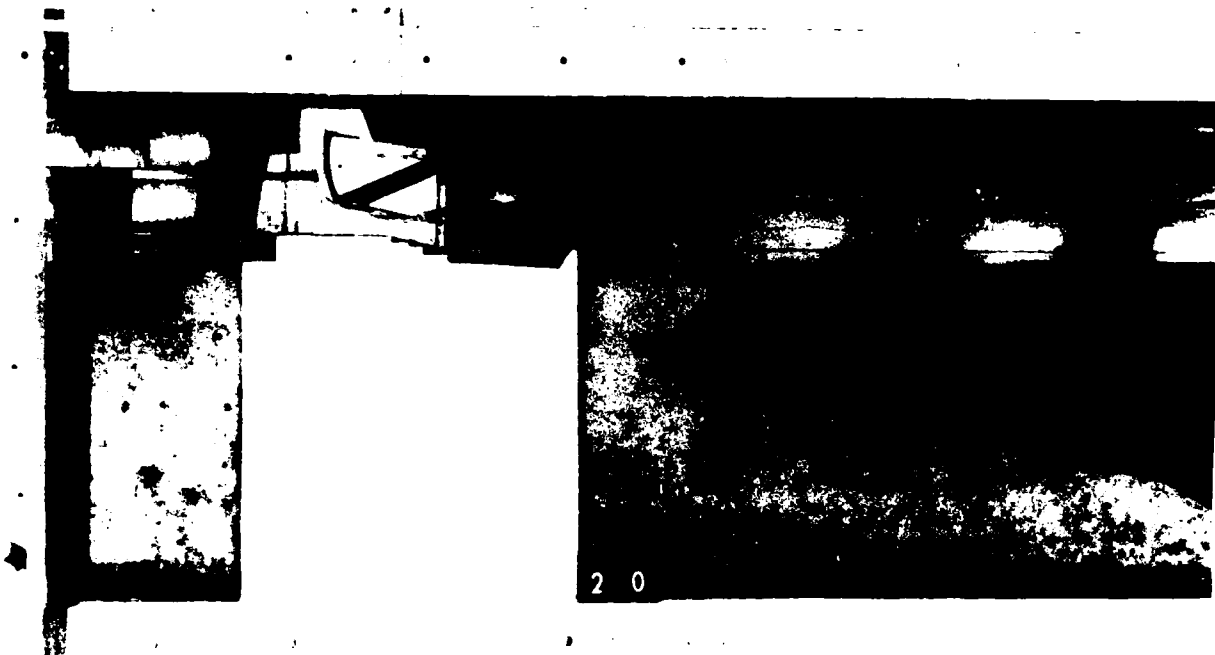
18. For the initial study of Lock and Dam 8, two portions of the spillway were tested in section models. The first section model consisted of one tainter gate bay, adjacent piers, half of the adjacent tainter gate bays, and a portion of the riverbed upstream and downstream of the structure. The second section model consisted of a roller gate and adjoining half gates. Figure 6 shows a side view of the models in operation. The objective of testing these section models was to determine the hydraulic conditions that caused the scour at Lock and Dam 8.

19. The model structure was made of sheet metal and placed in a 1-ft-wide glass-walled flume. Crushed coal or sand was used to simulate the streambed. Crushed limestone simulated the riprap aprons upstream and downstream of the structure.

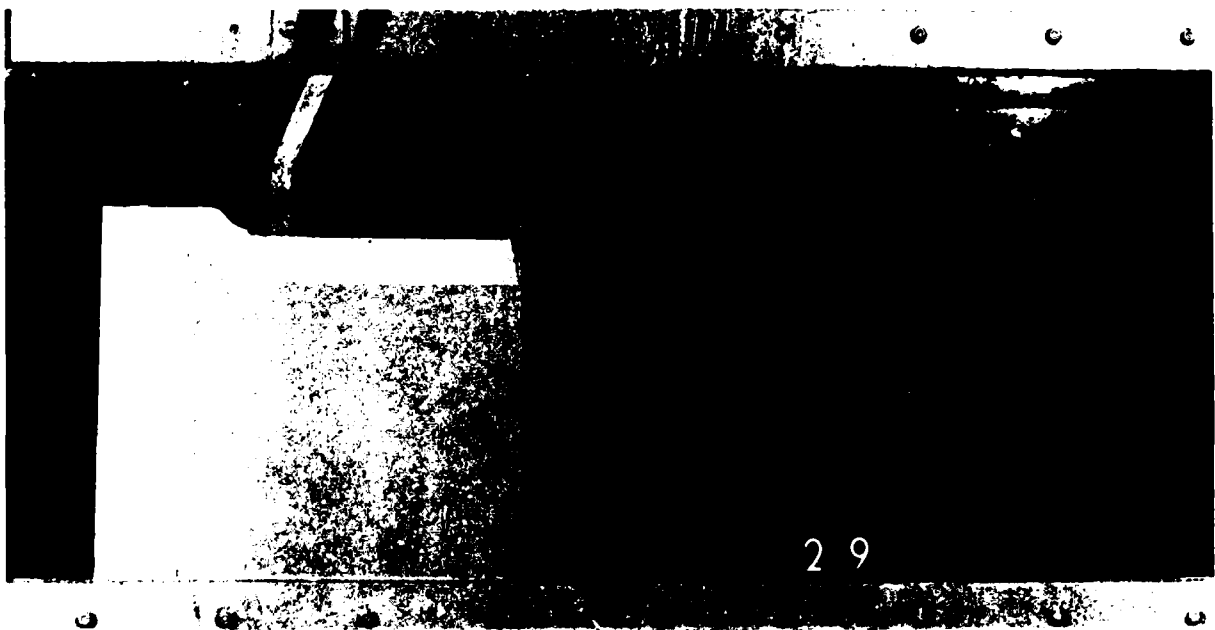
1:42-scale model

20. A section of spillway that included a roller gate was modeled with a scale of 1:42. This section model consisted of one and one-half roller gate bays and two and one-half tainter gate bays and the immediate vicinity upstream and downstream of the structure. Plate 1 shows a plan view of the section of structure modeled. Figure 7 shows a view of this model from downstream and upstream. This relatively large model was used to develop a riprap design that would provide scour protection against all probable causes of erosion (paragraph 26) at the Upper Mississippi River locks and dams.

21. The model structure, constructed from sheet metal and plywood, was placed in a flume with a plastic-sided test (observation) section. Additionally, this model was placed in a full-width flume (Figure 8) to simulate the

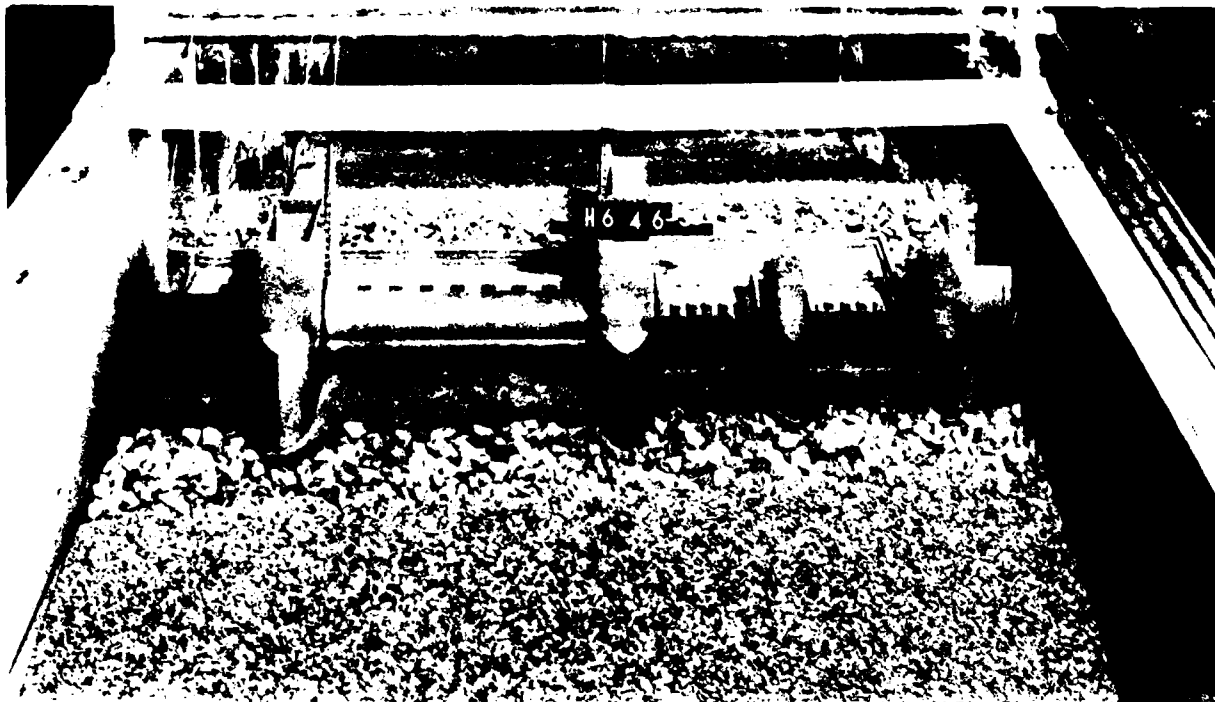


a. Tainter gate operation

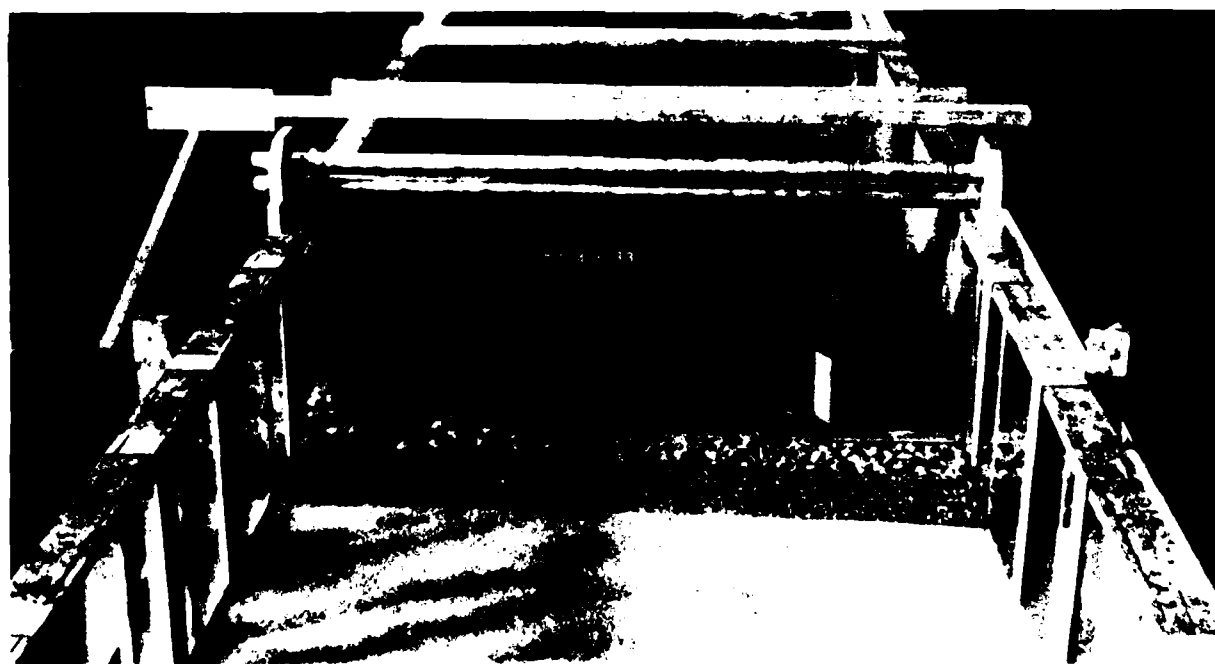


b. Roller gate operation

Figure 6. 1:70-scale section model in operation



a. View from downstream

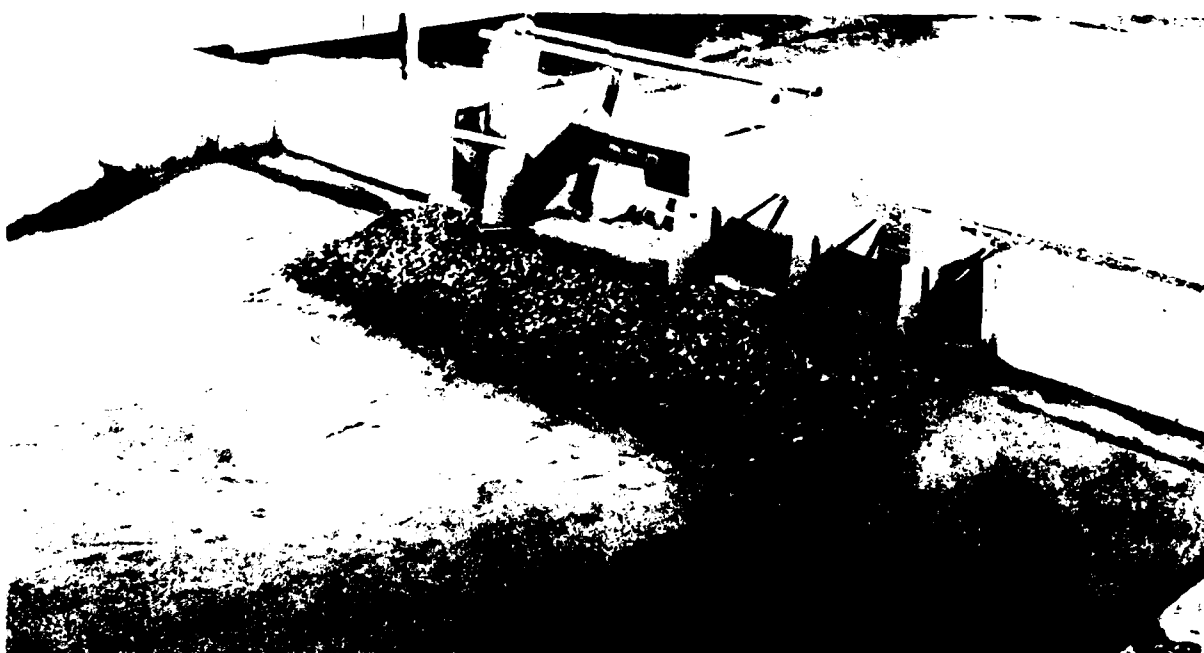


b. View from upstream

Figure 7. 1:42-scale section model



a. View from downstream



b. View from upstream

Figure 8. 1:42-scale model in full-width flume

actual river width at the structure. Thus, hydraulic conditions with single-gate operation would be more representative of actual prototype conditions. Sand was placed in the flume to simulate the riverbed. Crushed limestone reproduced the different-sized riprap investigated for erosion protection.

Lock and Dam 2 Model

22. Because of the unique design and operational characteristics of Lock and Dam 2, an overall model of this structure was constructed. The 20 tainter gates and the ungated crest were reproduced for testing. The lock portion of the model was nonoperational. The concrete stilling basins and the timber cribs filled with stone were also reproduced. Plate 2 shows the model plan and limits. This 1:42-scale model was used to develop a suitable scour protection for Lock and Dam 2.

23. The model was constructed from sheet metal, concrete, and wood. The riverbed was simulated with sand; crushed limestone reproduced the riprap in the model. Figure 9 shows a view of the model from downstream.

Testing Procedure

24. Of interest in each of the models used in this investigation were the hydraulic and geometric conditions that resulted in scour. In all the models, a movable bed, e.g., sand or crushed coal, was used so that hydraulic action could transport the bed material. The erosion and movement of this material were indicative of potential scour. The amount of erosion under given conditions was a qualitative indication of prototype degradation.

25. In the 1:70-scale model, the action that defined scour was the even movement of coal particles over the bottom of the flume. The failure of a riprap design in the 1:42-scale model was defined as the point when several of the individual rocks fluttered or were displaced and moved downstream. In either model, the hydraulic condition considered critical for incipient transport and potential riprap failure was determined. After an allotted amount of operation time (scaled from prototype), flow was stopped and the model inspected. Severity of the scour or adequacy of the riprap design was determined by visual observations during model operation and, after the test, visual inspection of the model and measurement of the depth of scour or thickness of riprap blanket.

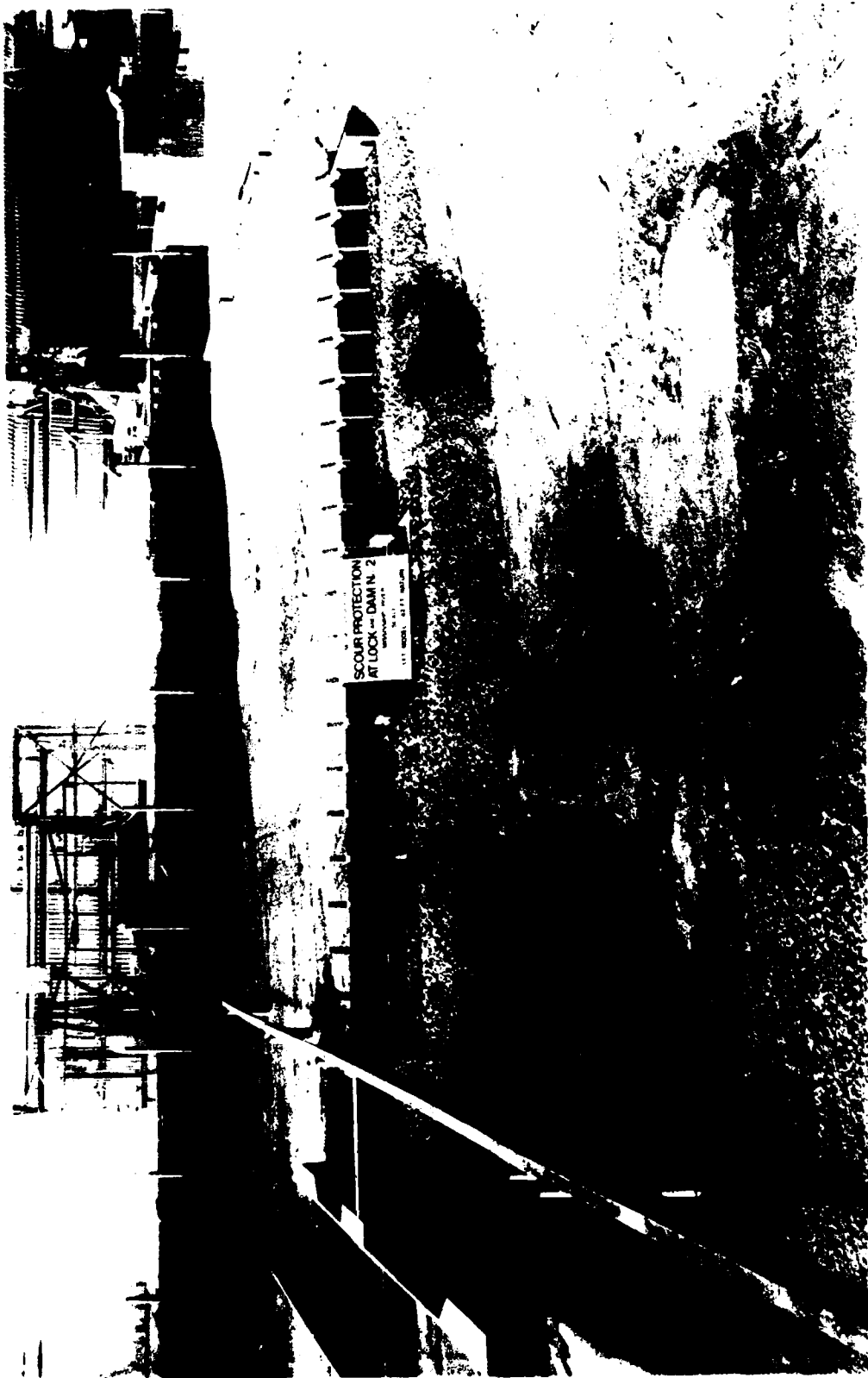


Figure 9. 1:42-scale model of Lock and Dam 2, view from downstream

PART III: RESULTS

Causes of Scour

26. The 1:70-scale model was used to evaluate probable causes of scour at the Upper Mississippi River projects. Initially, it was hypothesized that one of several conditions could contribute to the streambed erosion. The hydrologic and flow conditions considered likely candidates were uncontrolled spillway flow, controlled spillway flow with low tailwater, nonuniform gate operation, frazil ice formation with a "hanging" ice dam, and stratified flow. These conditions were simulated in the model or investigated in the prototype.

27. It was speculated that perhaps a coldwater density current caused or contributed to the scour downstream of the structure. However, a field study at Locks and Dams 6 and 8 indicated that water temperature was essentially constant from surface to bottom. Thus, no density current was apparent. It is doubtful that, in this case, sufficient density difference of the flowing water could occur that would spawn a density current with velocity large enough to cause scour.

28. In the very cold weather of the Upper Mississippi Valley, the water in the river becomes "super-cooled." The temperature of the water actually falls below freezing, but the water cannot solidify because of its movement. As a result, frazil ice (minute ice particles) forms in the body of the flowing water and is transported downstream. The frazil ice particles are extremely adhesive and will readily stick to solid ice. It was conjectured that the frazil ice was passing through the structure and stilling basin and then adhering to the underside of the leading edge of the downstream ice pack. Over a period of time the buildup of the frazil ice would form a constriction to flow (an inverted or hanging ice dam). The increased streambed velocities due to this condition might cause the downstream erosion.

29. Simulation of the ice cover and hanging dam in the 1:70-scale model indicated that the potential for scour was high. However, review of ice records at the prototypes indicated that the downstream ice cover rarely extended up to the scour area and that meteorologic conditions favorable for frazil ice formation were extremely infrequent. The buildup of ice for an ice dam was not evident; fishermen used the downstream area extensively for ice fishing,

and thick frazil ice would make fishing extremely difficult. Although the physical model indicated that a hanging ice dam could contribute to the scour, it was concluded that such an occurrence was unlikely.

30. In April and May 1965, flood flows required that all the spillway gates be fully opened. This large discharge was a suspected cause of the scour at Lock and Dam 8. The flood hydrograph was reproduced in the model and simulated the rise, peak, and fall of the flood discharge. The scour pattern that resulted in the movable bed indicated only a minor amount of streambed degradation. The extent of this scour was insignificant compared with that which exists in the prototype. Stilling basin performance was satisfactory, and, therefore, severe local scour would not be expected. This suggests that the scour hole that exists in the prototype was not the result of major discharges such as the 1965 flood when uncontrolled spillway releases occurred.

31. Stilling basin performance and scour tests were conducted for controlled uniform releases over a wide range of tailwater elevations and gate openings. The 1:70-scale model indicated that, with a much-lower-than-normal tailwater, flow exiting the stilling basin could induce severe scour downstream (Figure 10). A review of historical records revealed that tailwater elevations had never been as low as those that caused severe scour in the model. It was therefore concluded that controlled uniform flow was not a major contributor to the scour at Lock and Dam 8 or other Upper Mississippi projects.

32. Nonuniform gate operation, including single-gate operation, was tested in the 1:70-scale model. It was discovered that with nonuniform gate operation, scour could be induced upstream and downstream of the structure with much higher tailwater than with uniform gate openings. This was particularly true for single-gate operation. Lock operators indicated that single-gate operation was routinely used to flush ice and debris through the spillway. It appears that the worst case hydraulic conditions, which probably caused scour at these structures, are single-gate operations with a large gate opening.

33. Based on the results of the tests conducted in the 1:70-scale model, the St. Paul District adopted single-gate operation with minimum tailwater as the critical design condition for developing a stable riprap protection plan for the Upper Mississippi projects. The actual test criteria are based upon operations with one gate open halfway and then fully open subject

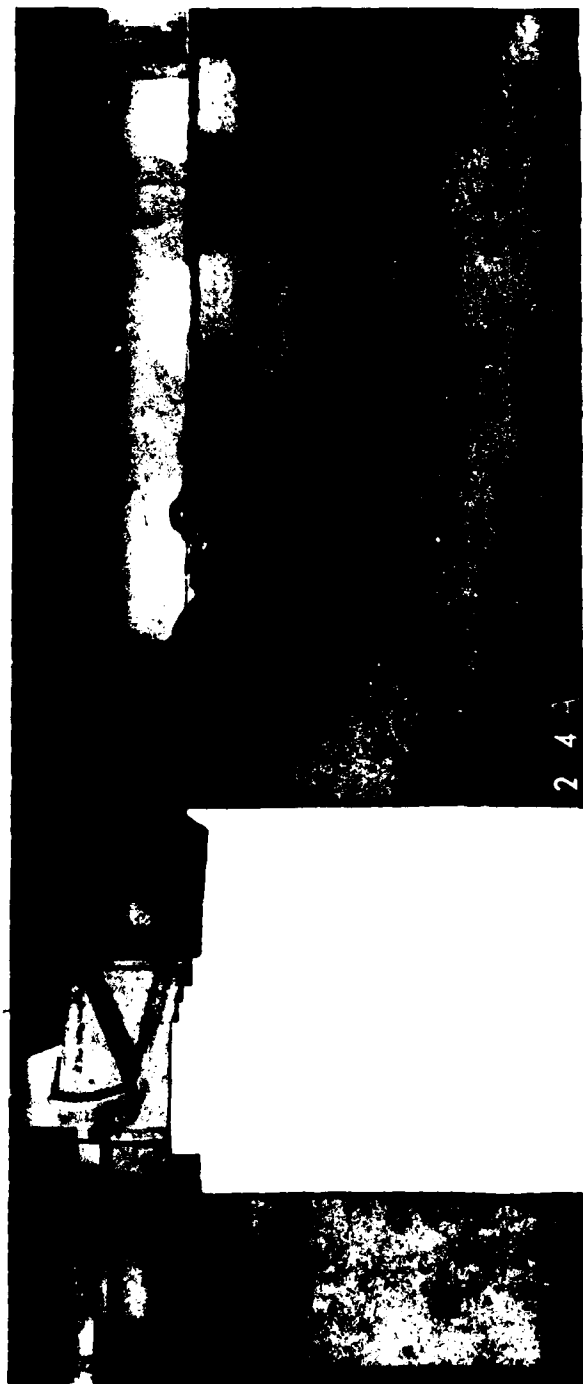


Figure 10. Flow and scour conditions in 1:70-scale section model with uniform controlled flow, lower than normal tailwater

to normal pool and minimum tailwater conditions (Figure 11). The design criteria permitted no damage to the stone protection for extended operations with a single gate, one-half open (6 ft for a roller gate and 4.5 ft for a tainter gate). Only minor damage was permitted with a single gate fully opened. This criterion was in compliance with current Corps of Engineers requirements for design of stilling basins and stone protection at navigation dams (Office, Chief of Engineers (OCE) 1983). These criteria were used in the 1:42-scale model for testing various riprap designs.

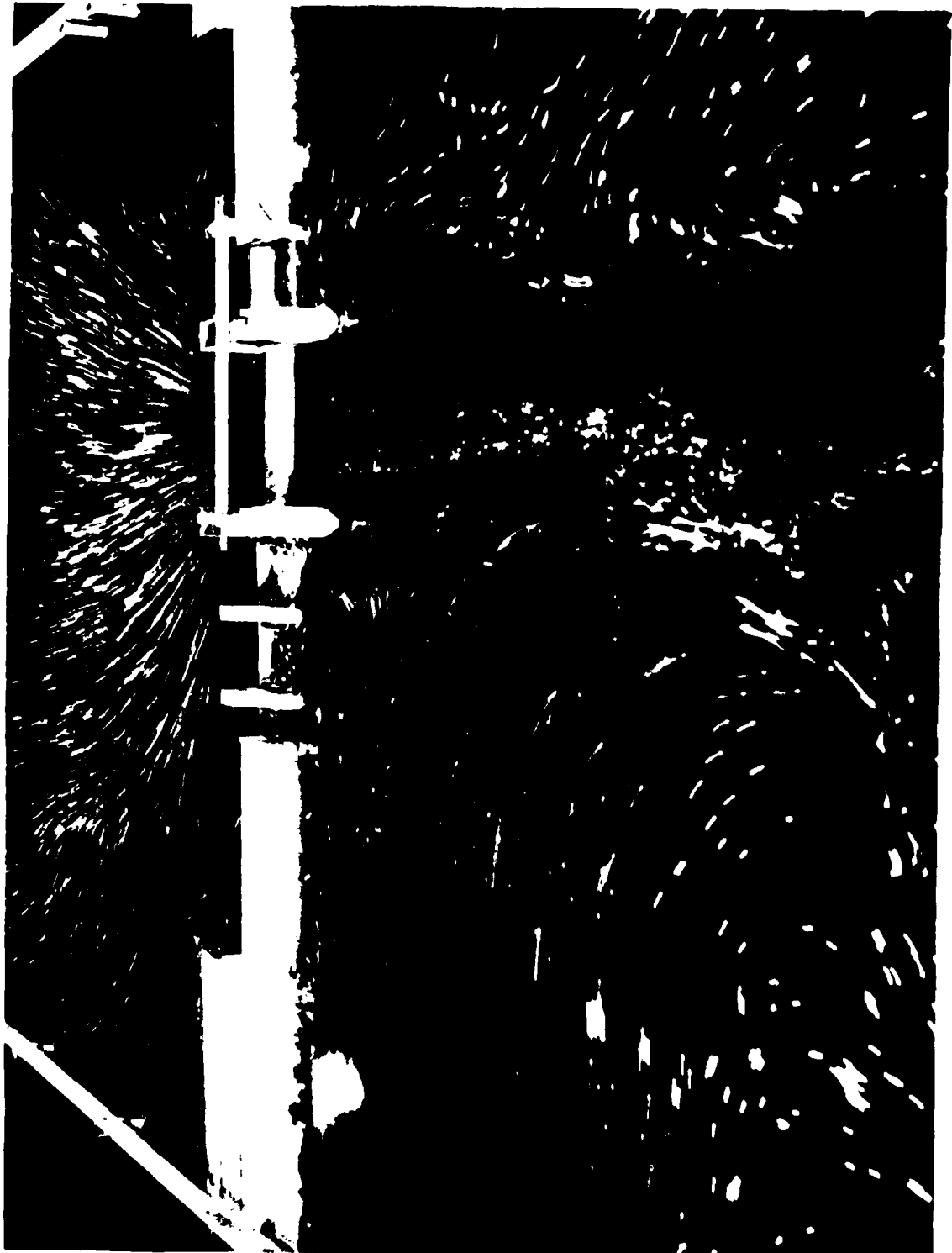
Locks and Dams 3-10 Scour Tests

34. Initially, tests were conducted in the 1:42-scale section model with a movable bed of sand to determine the minimum extent of protection required for stabilizing the scour slopes. Profiles of the scour holes that developed upstream and downstream of the spillway for the single gate fully opened test conditions are shown in Figures A1-A4 in Appendix A. The deepest scour always occurred downstream of the gate piers. The results of these tests indicated that minimum horizontal lengths of stone protection would have to be at least 65 ft upstream of the gate sill and 125 ft downstream of the stilling basin end sill. This extent of riprap would provide adequate stabilization of the existing scour slopes.

Conceptual scour protection designs

35. Six protection designs were considered for stabilizing the scour. They are as follows: Type I design protection, 42-in. riprap upstream and downstream; Type II design protection, 30-in. riprap upstream and downstream; Type III design protection, quarry stone fill capped with 30-in. riprap; Type IV design protection, quarry stone fill of entire scour hole capped with 30-in. riprap; Type V design protection, articulated concrete mattress; Type VI design protection, gabions. Figure 12 shows schematics of these design concepts.

36. The articulated concrete mattress (Type V) was not recommended because of its high cost. The facility that manufactures the mattress is normally stationed in the Lower Mississippi River. Thus, extreme cost would be incurred in moving the mat-sinking unit to the Upper Mississippi projects. Gabions (Type VI), which are rock-filled wire baskets, were not recommended because of their high cost relative to loose quarry stone.



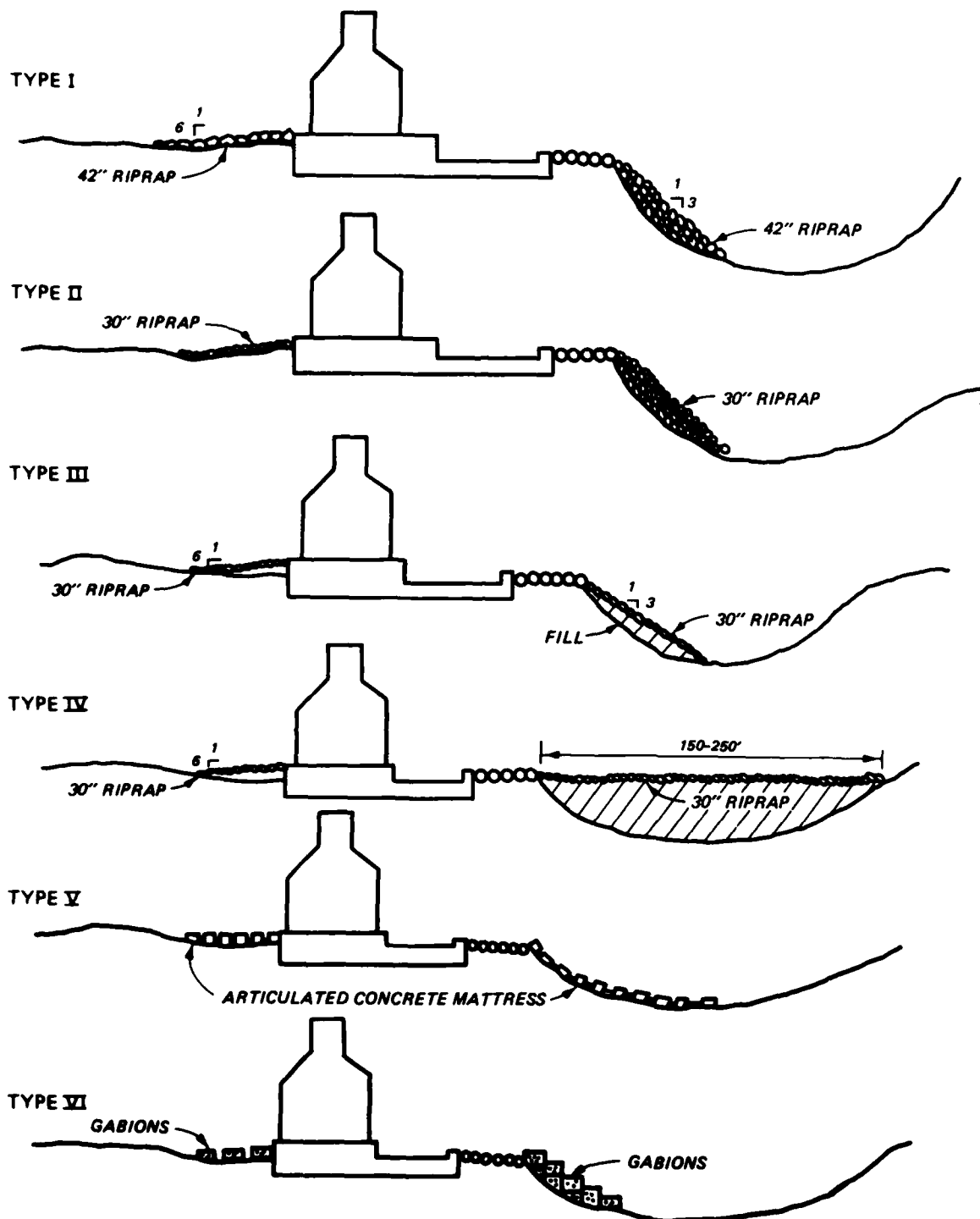


Figure 12. Conceptual scour protection designs

37. Because of the huge volume of the scour hole, it was not feasible to fill the entire erosion area with fill material or stone. Therefore, Type IV design protection was rejected since it required filling the scour hole with quarry stone and then capping the fill with a 30-in-diam riprap.

38. The design protection of Types I-III appeared to have the greatest potential for stabilizing the erosion by protecting the existing scour slopes. However, even with the reduced amount of fill required by these designs, the amount of stone required would be extremely large. The use of available material was a fiscal necessity. Quarry stone is more readily available than the 42- or 30-in.-diam riprap; thus, Types I and II design protection were not recommended because of the expense of filling with the large riprap. The Type III design protection concept was adopted for detailed testing in the 1:42-scale model.

39. The fill material (quarry stone) and the larger apron riprap are available from existing quarries and will be used for repair of the scour areas adjacent to the spillways. The apron riprap will be used to reconstruct the spillway aprons directly upstream and downstream of the structures. The quarry stone will be used as the filler and bedding material for the apron riprap and for reconstructing bed slopes in severely scoured areas. Quarry stone will also serve as a protective cover for stabilizing the more mildly sloped portions of the existing scour holes.

Riprap design

40. Tests in the 1:42-scale model indicated that apron riprap with a minimum thickness of 46 in. and a gradation of $W_{100} = 970$ lb, $W_{50} = 400$ lb, and $W_{15} = 200$ lb (Type A-1 apron riprap) will provide stable protection for the fill material. The underlayer of quarry stone fill tested in the model had a minimum thickness of 21 in. with a gradation of $W_{100} = 80$ lb, $W_{50} = 24$ lb, and $W_{15} = 9.8$ lb (Type Q-1 quarry stone). Figures A5 and A6 in Appendix A show these gradations graphically. It must be noted that an exact simulation of the fill material or quarry stone available for use in the prototype may not be possible because the gradation of the prototype material may vary slightly.

41. The gradation of quarry stone that is readily available from local quarries is approximately $W_{100} = 650$ lb, $W_{50} = 95$ lb, and $W_{15} = 11.5$ lb (Figure A6, Appendix A) (Type Q-2 quarry stone). Because of this availability, the St. Paul District wanted to limit the combined thickness of apron

riprap and fill material to 6 ft: a 42-in.-thick layer of apron riprap on top of a 30-in.-thick layer of quarry stone. Therefore, it was necessary to determine an adequate gradation design for the 42 in. of apron riprap.

42. For protection upstream and downstream of the tainter gate bays and upstream of the roller gate bays, 42 in. of Type A-1 riprap satisfied the single-gate test criteria. However, this riprap failed when subjected to the single-gate test criteria downstream of the roller gate bays. A heavier riprap with a gradation of $W_{100} = 970$ lb, $W_{50} = 620$ lb, and $W_{15} = 480$ lb (Type A-2 apron riprap, Figure A5) and 42-in. thickness is recommended for these areas.

Geometry of protection

43. During model tests of the gradation designs discussed above, two geometric design concepts were developed that meet or exceed the minimum requirements defined by the adopted test criteria. The recommended design is dependent on whether the existing scour slope upstream from the gate sill or downstream from the end sill is steeper or flatter than a 1V on 3H slope. This slope was found to be stable in several studies at the US Army Engineer Waterways Experiment Station (WES) for structures on the Ohio (Hite 1982, 1984a, 1984b), Monongahela (Hite 1985a), and Allegheny Rivers (Hite 1985b). Slopes steeper than 1V on 3H are less stable because stones move more readily by rolling down the slope. With flatter slopes, the stones are subjected to more of the turbulent flow downstream from the stilling basin. Also, with flatter slopes, more scour occurs in the erodible material downstream from the riprap and causes raveling at the end of the protective blanket.

Recommended design

44. For a scour slope in the prototype of 1V on 3H or flatter, a minimum of 46 in. of Type A-1 apron riprap should be placed on top of 21 in. of Type Q-1 quarry stone. As an alternative, 42 in. of Type A-2 apron riprap could be placed on 30 in. of Type Q-2 quarry stone. For either gradation design, the quarry stone should be placed on the existing slope for a horizontal distance of 65 ft upstream of the gate sill and for at least 125 ft downstream from the end sill. The scoured prototype aprons should be reconstructed with the apron riprap and should extend for at least 45 ft upstream of the gate sill and for at least 70 ft downstream of the end sill. Figures 13 and 14 show schematics of this design.

45. For a scour slope steeper than 1V on 3H, the existing slope should be reconstructed to a 1V on 3H slope with a minimum thickness of 21 in. of

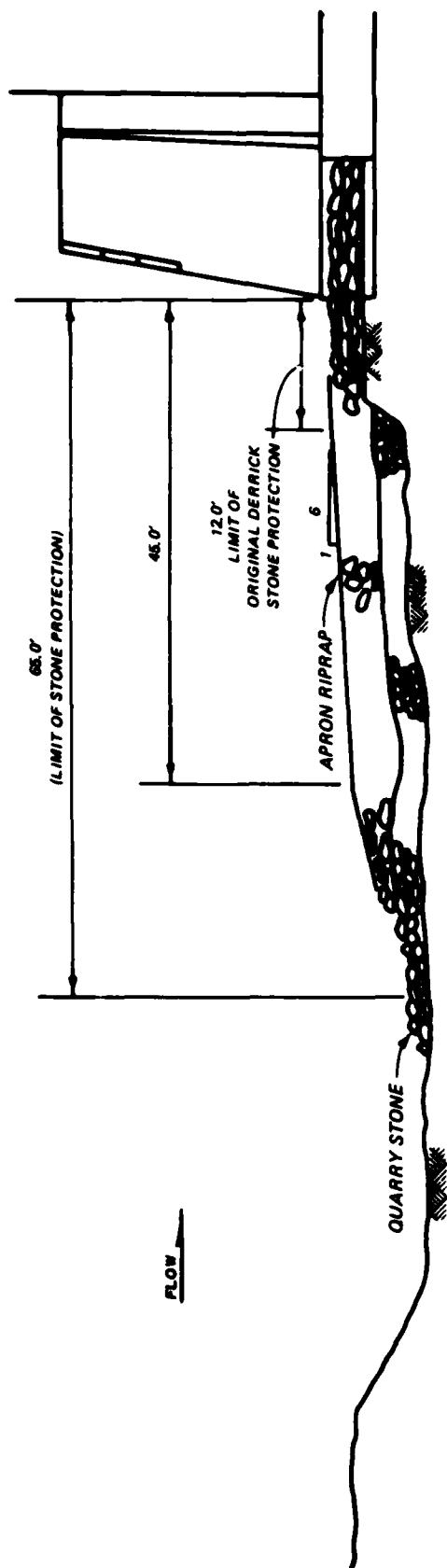


Figure 13. Upstream protection design for scour slopes of 1V on 3H or flatter

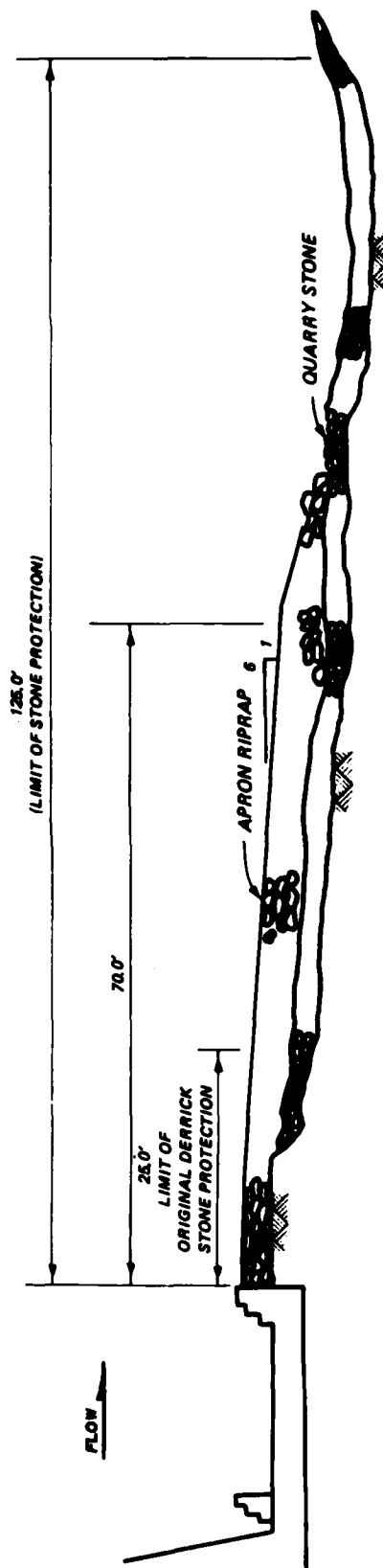


Figure 14. Downstream protection designs for scour slopes of 1V on 3H or flatter

Type Q-1 quarry stone. The aprons should be repaired with a minimum thickness of 46 in. of Type A-1 apron riprap placed on top of the quarry stone for a horizontal distance of at least 30 ft upstream of the gate sill and extend down the reconstructed slope to an elevation 5 ft below the top of the apron riprap (Figure 15). Downstream, the apron riprap should extend a horizontal distance of at least 40 ft downstream of the end sill and then extend down the reconstructed slope to an elevation 10 ft below the top of the apron riprap (Figure 16).

46. If the Type Q-2 quarry stone is used to reconstruct the slope to 1V on 3H, Type A-2 apron riprap should extend upstream and downstream of the structure for a horizontal distance of 25 ft. The riprap should then extend down the slope for horizontal distances upstream and downstream of 15 and 30 ft, respectively (Figures 17 and 18).

47. A photograph of the recommended conceptual design of the downstream protection in the 1:42-scale model is shown in Figure 19. It must be emphasized that the sizes and gradations simulated in the model were the minimum that provided stability. Any prototype material of equal or better size and gradation as discussed in paragraphs 40-42 is preferred and recommended.

Special considerations

48. For consistency in the geometry of the riprap protection and to provide adequate thickness of armoring near the structure without excavation, the horizontal dimension of the apron riprap was extended well beyond the limit of the original derrick stone. The horizontal lengths of protection, as determined in the physical hydraulic model study, provided optimum protection. Under other hydraulic circumstances, the downward slope of the riprap could be initiated at other locations such as the gate sill or stilling basin end sill.

49. St. Paul District personnel estimated that more than one season (low-flow summer period) would be required to complete installation of the riprap protection. Thus, the apron riprap was not scheduled to be placed over the fill material immediately. Therefore, tests were conducted in the 1:42-scale model to determine the adequacy of the fill material (Type Q-2 quarry stone) to withstand the single-gate operation design criteria. Tests were conducted to simulate an approximate 30-in.-thick layer of fill material 54 in. below the top of the roller and tainter gate end sills.

50. Test results indicated that the fill material in the areas upstream

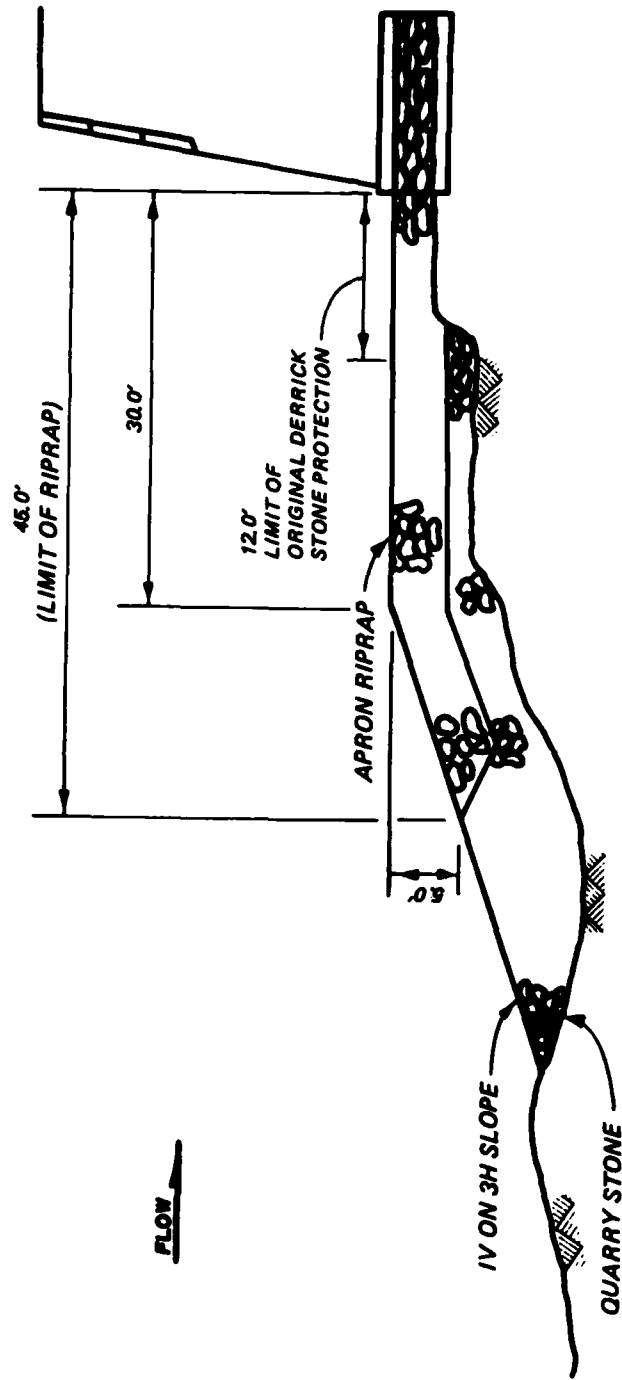


Figure 15. Upstream protection design for scour slopes steeper than 1V on 3H, Type A-1 riprap

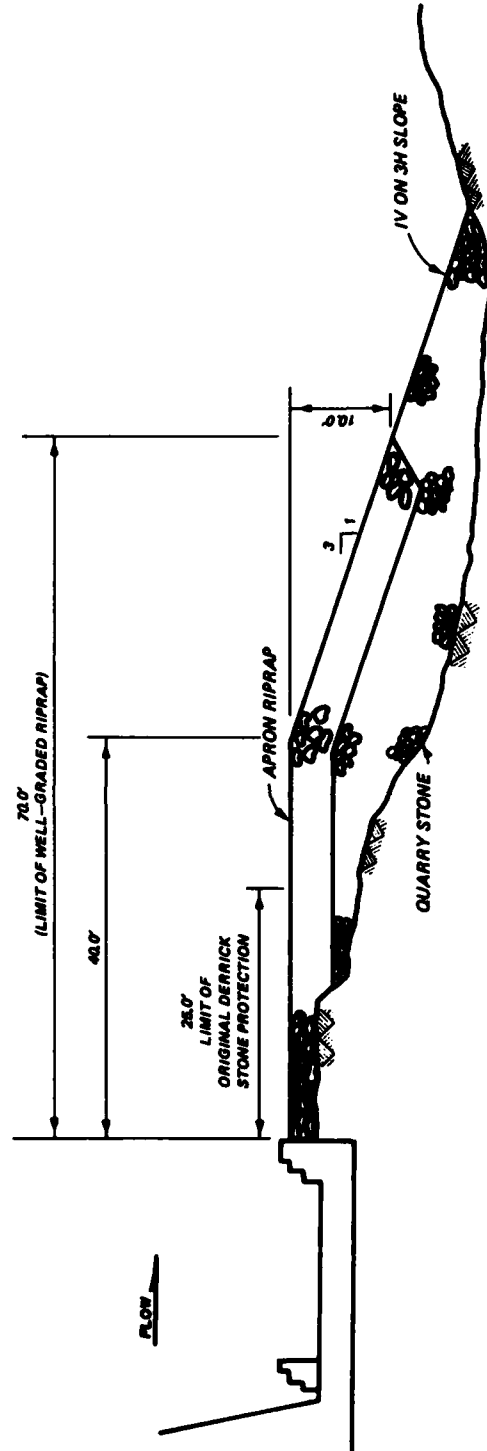


Figure 16. Downstream protection design for scour slopes steeper than 1V on 3H, Type A-1 riprap

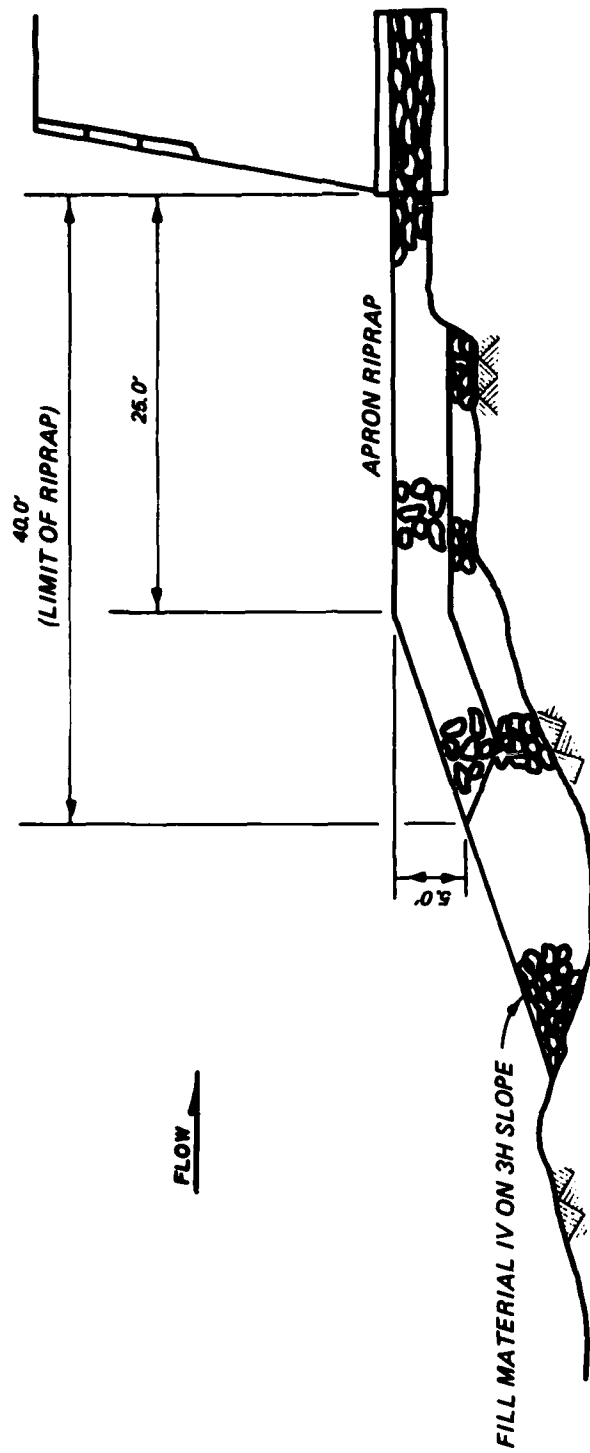


Figure 17. Upstream protection design for scour slopes steeper than 1V on 3H, Type A-2 riprap

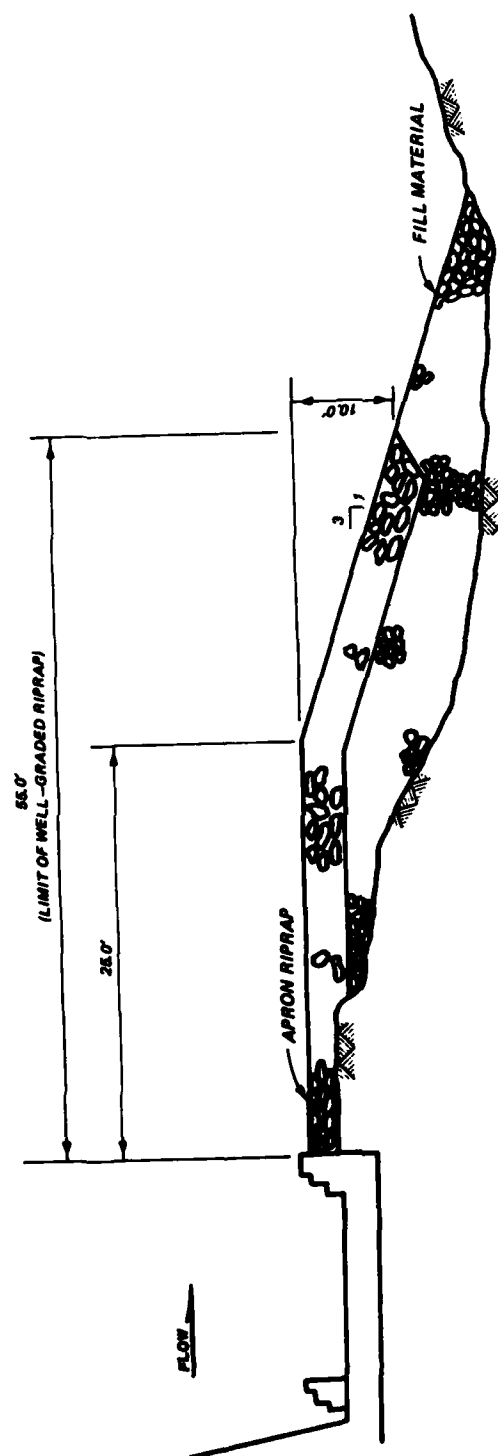


Figure 18. Downstream protection design for scour slopes steeper than 1V on 3H,
Type A-2 riprap

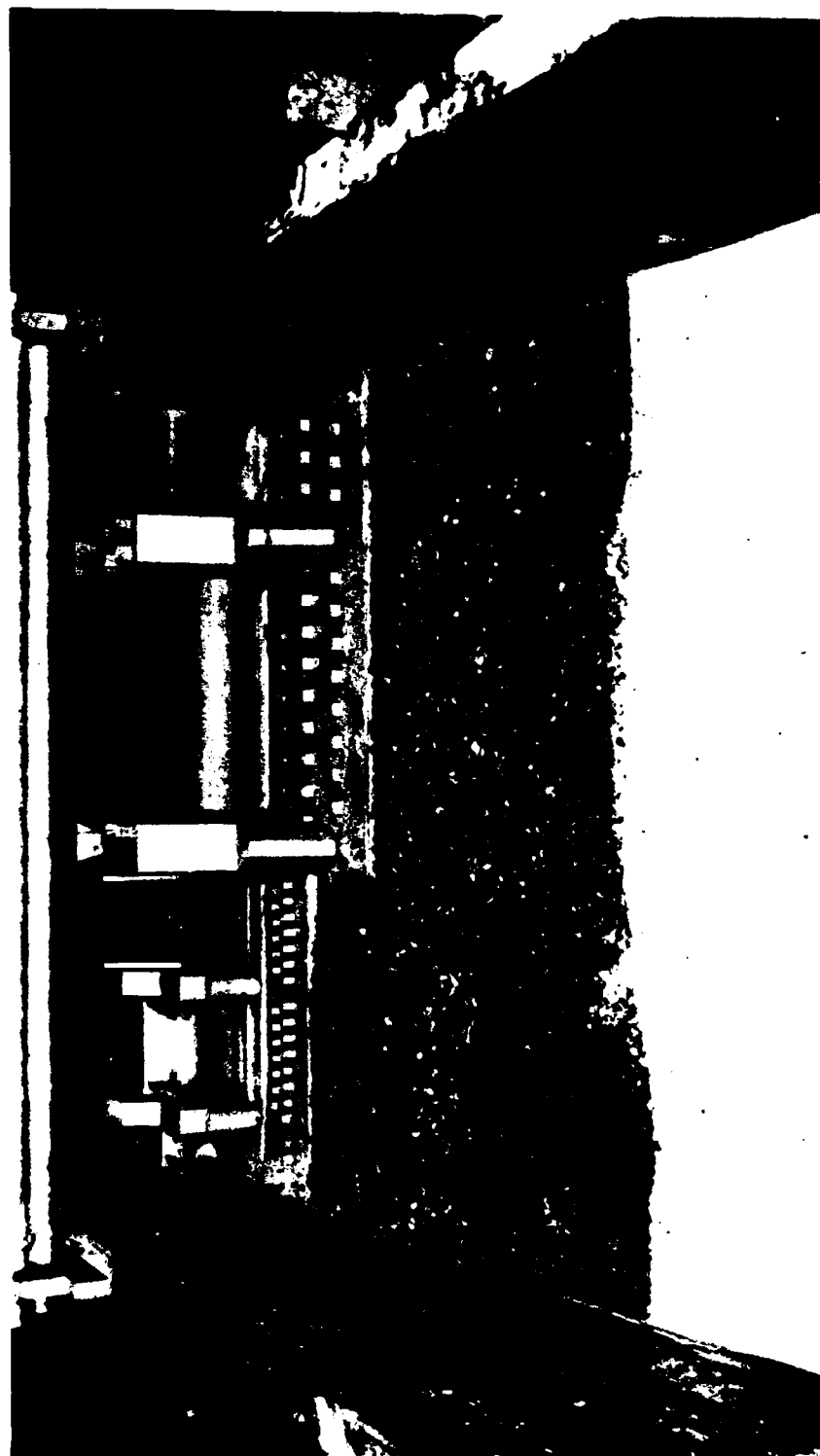


Figure 19. Recommended design placed in 1:42-scale section model

of the roller and tainter gate bays would withstand the half-open and full-open gate test criteria. Downstream of the spillway, the test criteria could only be met below the tainter gate bays. Operation of the roller gate was found to be limited to a maximum gate opening of 9.0 ft (or an equivalent discharge of approximately 15,500 cfs) with a normal headwater and minimum tailwater. Larger gate openings resulted in severe damage to the fill material on the apron downstream of the gate piers.

Lock and Dam 2

51. The variety of exit area configurations provided at Lock and Dam 2 is shown in Figure 5 and Plate 2. The riprap size and extent of stone protection required upstream and downstream of the spillway were determined by operating gates 2, 6, 10, 17, 18, and 19 with the full- and half-open gate criteria for normal pool and minimum tailwater. A movable sand bed in the model was used to estimate the extent of riprap protection required. The Type III design concept discussed in paragraph 38 was also adopted for use at Lock and Dam 2.

Upstream protection

52. Tests indicated that Type A-1 apron riprap with a thickness of 42 in. placed over Type Q-1 quarry stone with a thickness of 21 in. would meet the minimum requirements of the test criteria when installed upstream of the spillway. Layout of this riprap is illustrated in Figure 13. The apron riprap should extend at least 45 ft upstream of the gate sill while the quarry stone should extend at least 65 ft upstream of the gate sill.

53. Tests were also conducted to ensure the stability of the upstream apron when subjected to staggered gate operation. The gates were operated using the full-open gate criterion with alternating open and closed gates. Even though such operation is unlikely in the prototype, this provides a severe test to check the stability of the upstream apron. These tests indicated that the upstream apron riprap and quarry stone described in the preceding paragraph would remain stable when subjected to staggered gate operation.

Downstream protection

54. Tests to determine the size of stone protection required downstream of the spillway indicated that the heavier Type A-2 apron riprap with a thickness of 42 in. would meet the test criteria. For scour slopes flatter than 1V on 3H, a minimum thickness of 21 in. of Type Q-1 quarry stone should be placed

on the existing slope and capped with 42 in. of Type A-2 apron riprap. The quarry stone and apron riprap should extend for at least 125 and 70 ft, respectively, downstream of the timber cribs similar to the design shown in Figure 14.

55. For scour slopes steeper than 1V on 3H, the quarry stone will serve as the filler and bedding for the apron riprap. Thus, the slope should be reconstructed with quarry stone to 1V on 3H. Apron riprap should extend horizontally for 40 ft downstream of the timber cribs and then down on the 1V on 3H slope for a horizontal distance of 30 ft. This geometric design is similar to that shown in Figure 16. As noted in paragraph 48, the extent of the horizontal protection was included to provide optimum protection for the full range of site-specific hydraulic conditions.

56. A prototype survey and model tests with the movable sand bottom indicated the necessity to stabilize the left bank downstream of the spillway. Scour potential was very severe in this area when gate 19 was operated in the full-open position with normal headwater and minimum tailwater. Tests conducted to determine an acceptable riprap design indicated that a minimum gradation of $W_{100} = 970$ lb, $W_{50} = 620$ lb, and $W_{15} = 480$ lb (Type A-2) would remain stable when constructed to a 1V on 2H slope.

57. The left bank was reconstructed permanently to close off gate 20 by initiating the toe of the slope at the landward pier of gate 19 (Figure 20) as requested by the St. Paul District. The 1V on 2H slope was extended along the left bank for approximately 500 ft downstream of the structure to finally tie

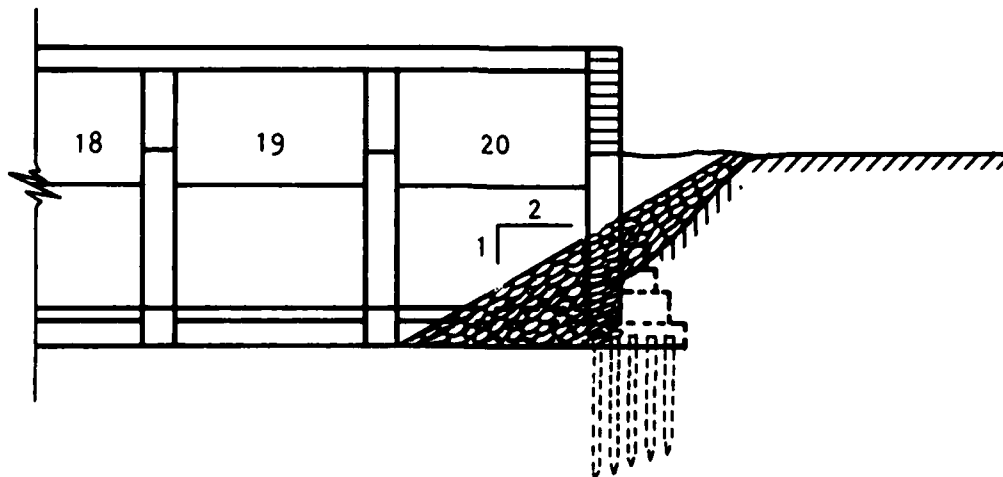


Figure 20. Reconstruction of left bank, Lock and Dam 2, view from downstream

in with the existing bankline (Figure 21). The toe of the slope was protected by extending the Type A-2 riprap and Type Q-1 quarry stone downstream of gates 18 and 19 as shown in Figures 21 and 22.

Filter Design Recommendations

58. Based on Corps of Engineers criteria for riprap filter design (OCE 1978), the Type Q-1 quarry stone with a W_{50} of 24 lb should have a W_{100} of about 156 lb ($6.5 W_{50}$) and a W_{15} of about 1.5 lb ($0.065 W_{50}$). For the Type Q-2 quarry stone with a W_{50} of 95 lbs, W_{100} and W_{15} should be 6,175 and 6 lb, respectively, for good filtering characteristics. Thus, the gradations of Types Q-1 and Q-2 quarry stone do not provide good filtering characteristics. Apron riprap equal to or greater in size than that described in previous paragraphs will provide acceptable protection against scour. For good filtering characteristics, however, a riprap with a W_{50} of about 400 lb (Type A-1) should have a W_{100} of about 2,600 lb and a W_{15} of about 26 lb. Type A-2 riprap should have W_{100} of 4,030 lb and W_{15} of 40 lb. In order to provide minimum filtering capability and prevent leaching of the bed material through the stone protection, it is recommended that 5 to 10 percent by weight of the stone in the apron riprap and fill material be less than $0.02 W_{50}$. Without these fines, two filters would normally be required beneath the riprap to prevent leaching of soil through the protective stone. Incorporation of some fines in the riprap will assist in providing a better filter and stone protection. Filter cloth was not considered due to the difficulties of underwater placement.

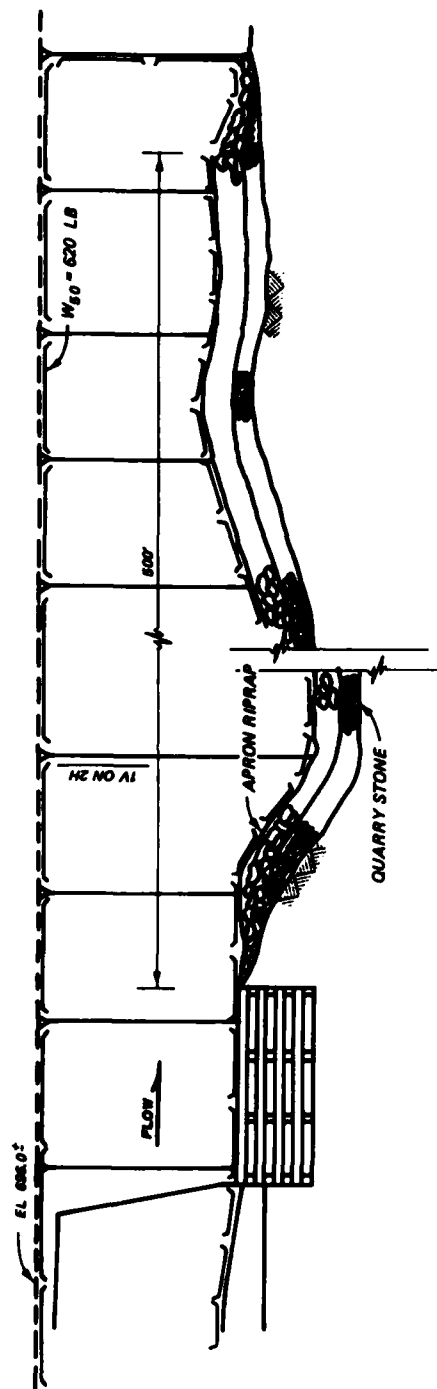


Figure 21. Extent of left bank reconstruction and protection downstream of gate 19, Lock and Dam 2

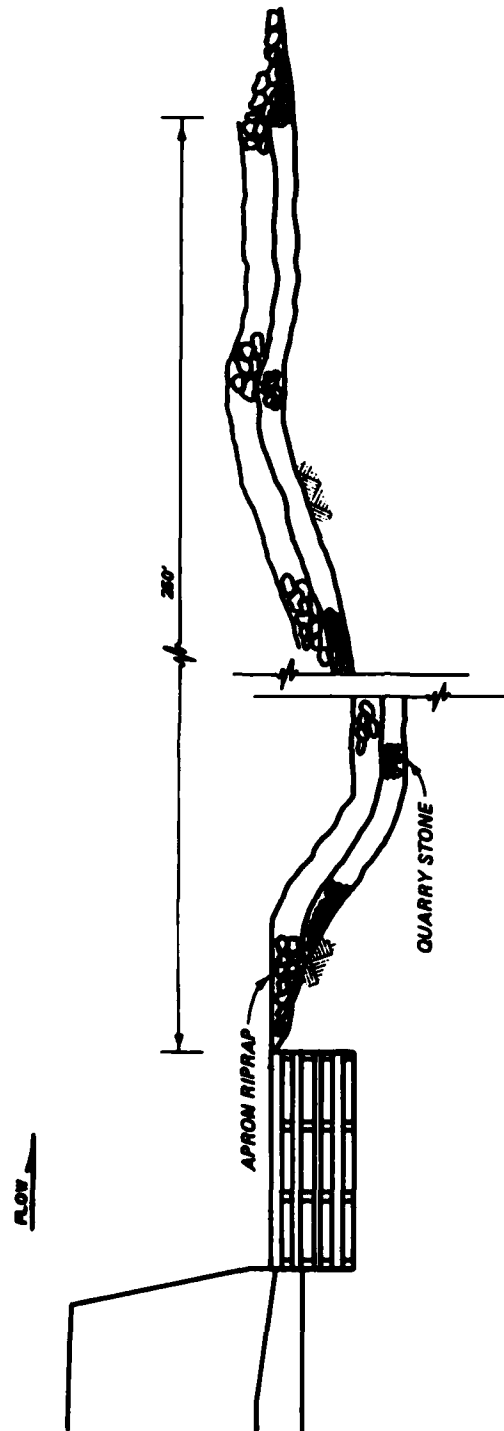


Figure 22. Design of protection recommended downstream of gate 18,
Lock and Dam 2

PART IV: SUMMARY AND RECOMMENDATIONS

59. Study of the scour problem at Locks and Dams 2-10 in a 1:70-scale model resulted in development of test criteria under which the riprap design would have to remain stable. Full-open and half-open gate operation for a single gate with normal pool and minimum tailwater were adopted as the critical hydraulic conditions for riprap design.

60. For Locks and Dams 3-10 recommended riprap design is dependent upon the scour slope. If the scour slope is flatter than 1V on 3H, it is recommended that quarry stone with a Type Q-1 gradation with a minimum thickness of 21 in. be placed beneath apron riprap with Type A-1 gradation with a thickness of 46 in. The quarry stone should be extended at least 65 ft upstream of the gate sill and at least 125 ft downstream of the stilling basin end sill. The apron riprap should provide protection for at least 45 ft upstream and 70 ft downstream.

61. For scour slopes steeper than 1V on 3H, Type Q-1 or Type Q-2 quarry stone should be used to reconstruct the streambed to 1V on 3H. The Type Q-1 quarry stone should be capped with a 46-in. layer of Type A-1 apron riprap. The Type A-1 apron riprap (with the Type Q-1 quarry stone) should extend at least 30 ft upstream of the gate sill and downstream for a horizontal distance of 40 ft. The riprap should extend down the reconstructed slopes as shown in Figures 15 and 16. If Type Q-2 quarry stone is used, Type A-1 apron riprap with a thickness of 42 in. will provide adequate scour protection upstream of a structure when placed over at least 30 in. of Type Q-2 quarry stone. Additionally, the Type A-1 riprap will provide adequate scour protection downstream of the tainter gate bays. However, Type A-2 apron riprap, which is heavier, is recommended for installation below the roller gate bays. For Type Q-2 quarry stone and either gradation, the apron riprap should extend horizontally upstream and downstream for 25 ft. The apron riprap should then extend down the 1V on 3H slope as shown in Figures 17 and 18.

62. Upstream of Lock and Dam 2, the Type A-1 apron riprap with a thickness of 42 in. placed over 21 in. of Type Q-1 quarry stone will meet the test criteria. Figure 13 shows the geometric layout of the riprap. Downstream of Lock and Dam 2, Type A-2 apron riprap with a thickness of 42 in. is recommended for stabilizing all slopes. For scour slopes flatter than 1V on 3H, Figure 14 depicts the geometric layout of the stone. For slopes steeper than

1V on 3H, Figures 15 and 16 give the protection layout.

63. Protection of the left bank at Lock and Dam 2 can be achieved with a Type A-2 apron riprap placed on a 1V on 2H slope. The bank slope should be extended downstream about 500 ft to tie into the existing bankline, thereby permanently closing off gate 20. Downstream of gates 18 and 19, Type A-2 riprap (42 in.) and Type Q-1 quarry stone (21 in.) should be used to protect the toe of the bank slope as shown in Figures 21 and 22.

64. In the design of a riprap protection plan that is subjected to highly turbulent flow, it is imperative that an adequate filter be provided to prevent leaching of material from underneath the riprap. The filtering capability of the Type Q-1 and Type Q-2 quarry stone to be placed underneath the protective riprap is questionable. Provisions should be made to ensure that, by weight, 5 to 10 percent of the stone in the fill material does not exceed more than $0.02 W_{50}$.

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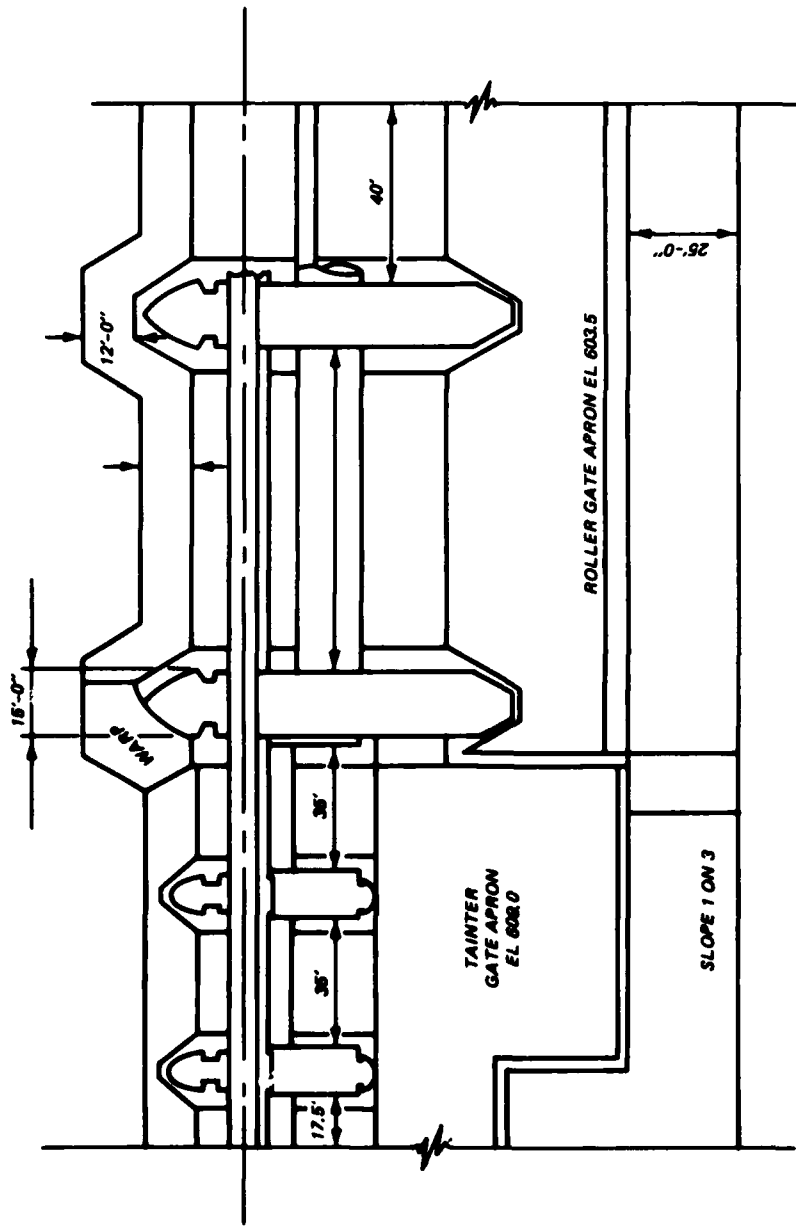
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MODEL LIMITS
LOCK AND DAM 8
1:42 SCALE

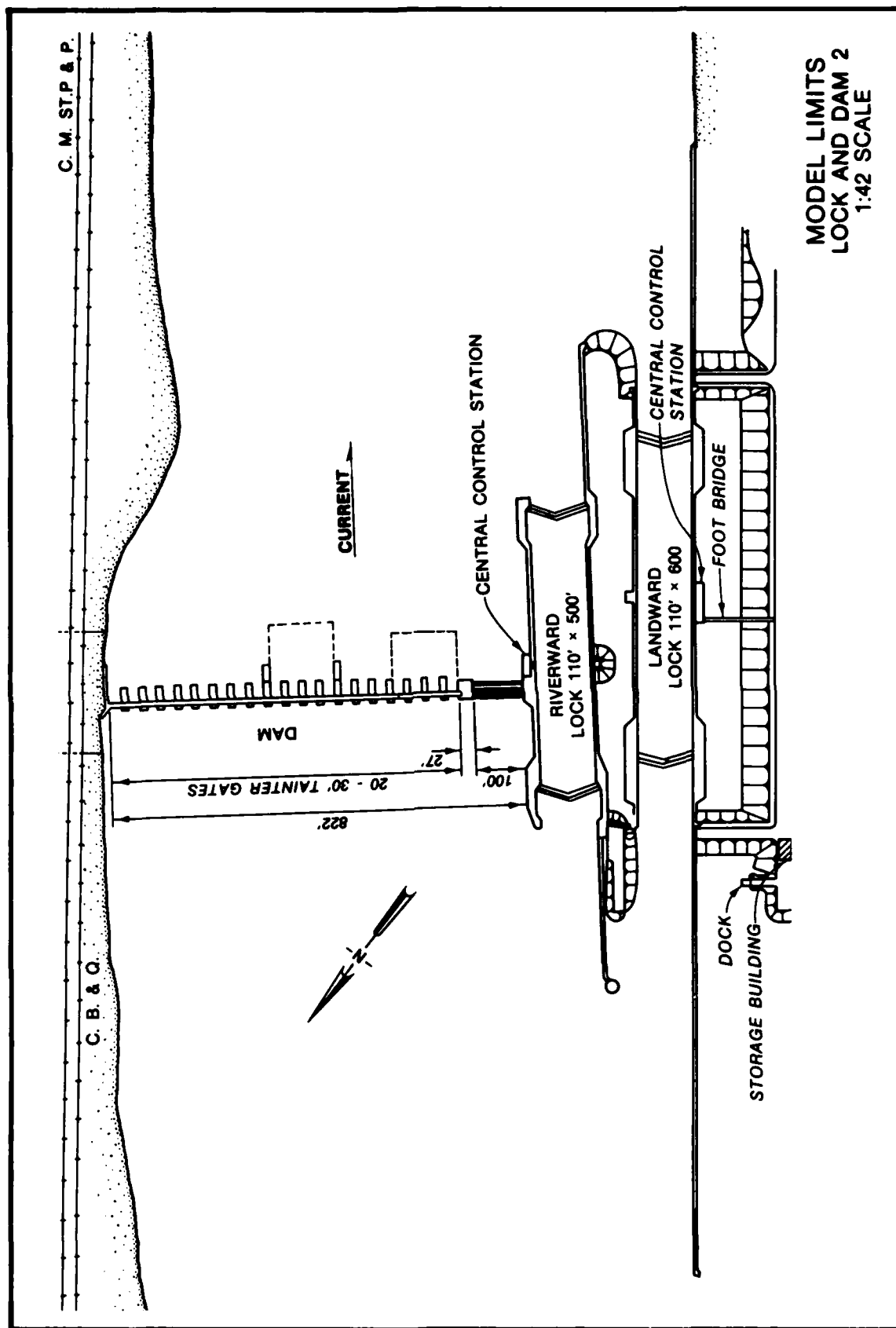


PLATE 2

APPENDIX A: SUPPLEMENTARY FIGURES

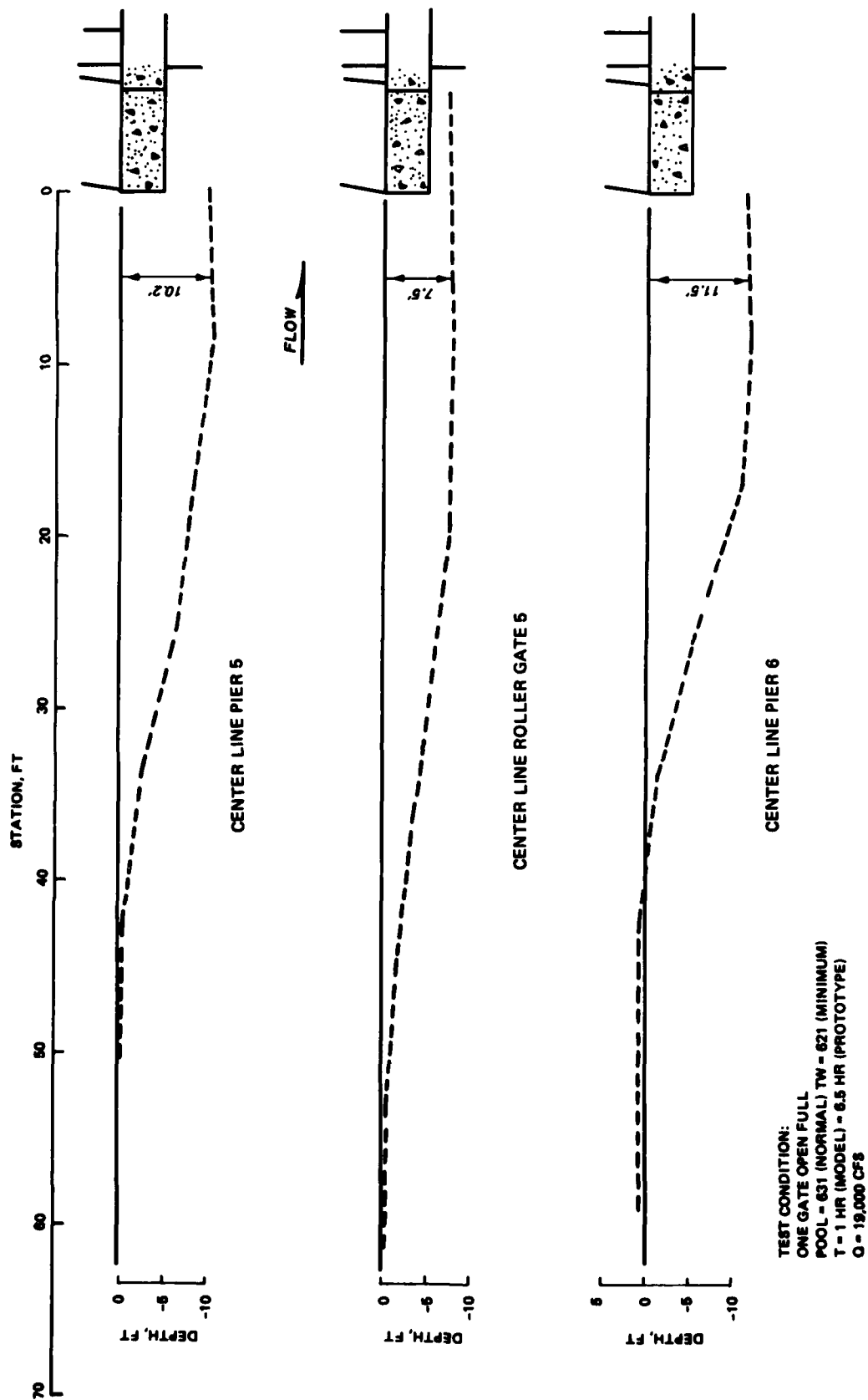
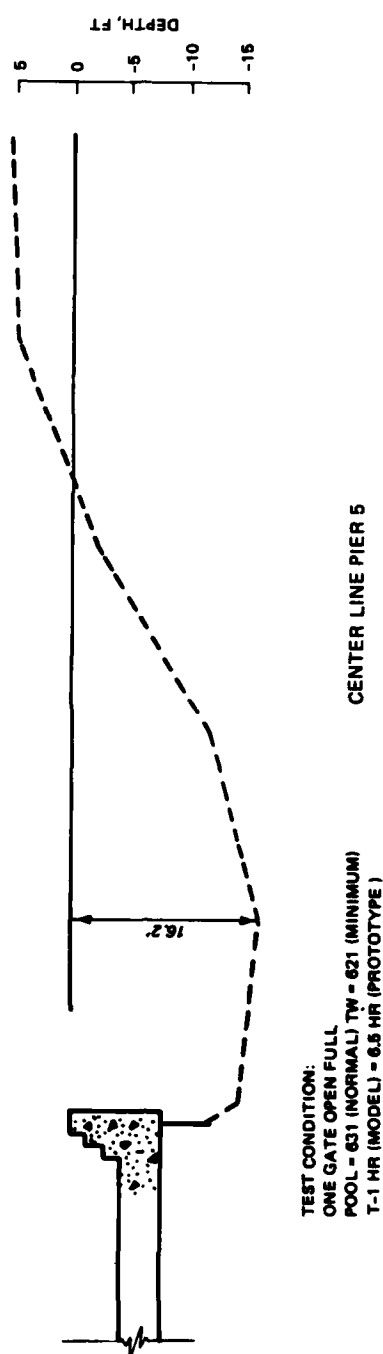
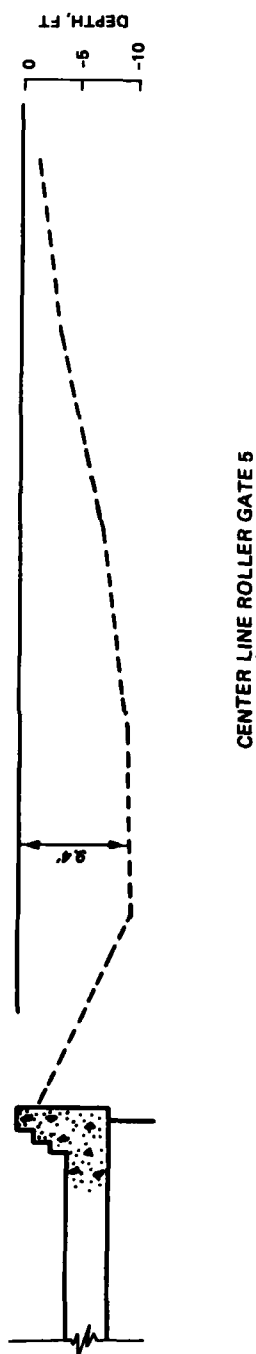
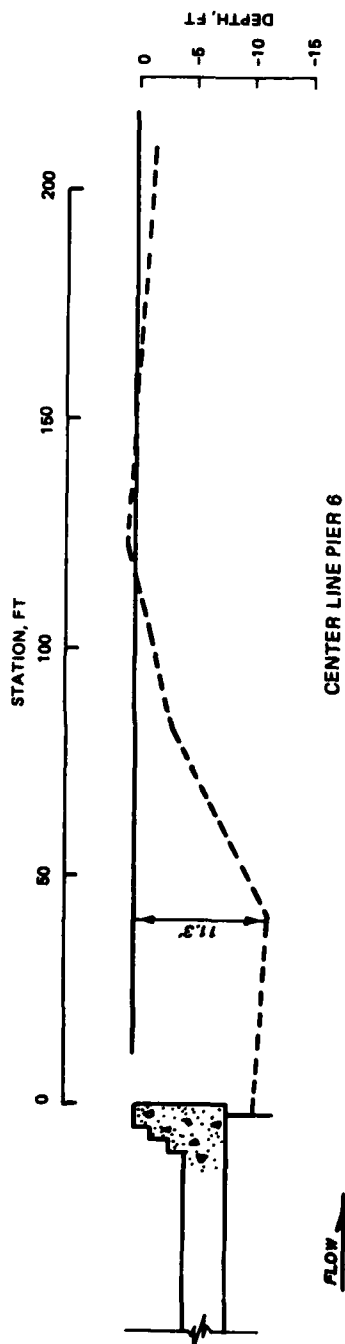


Figure A1. Scour patterns in 1:42-scale model upstream of roller gate 5 and adjacent piers



TEST CONDITION:
 ONE GATE OPEN FULL
 POOL - 631 (NORMAL) TW - 621 (MINIMUM)
 T-1 HR (MODEL) - 6.5 HR (PROTOTYPE)

Figure A2. Scour patterns in 1:42-scale model downstream of roller gate 5 and adjacent piers

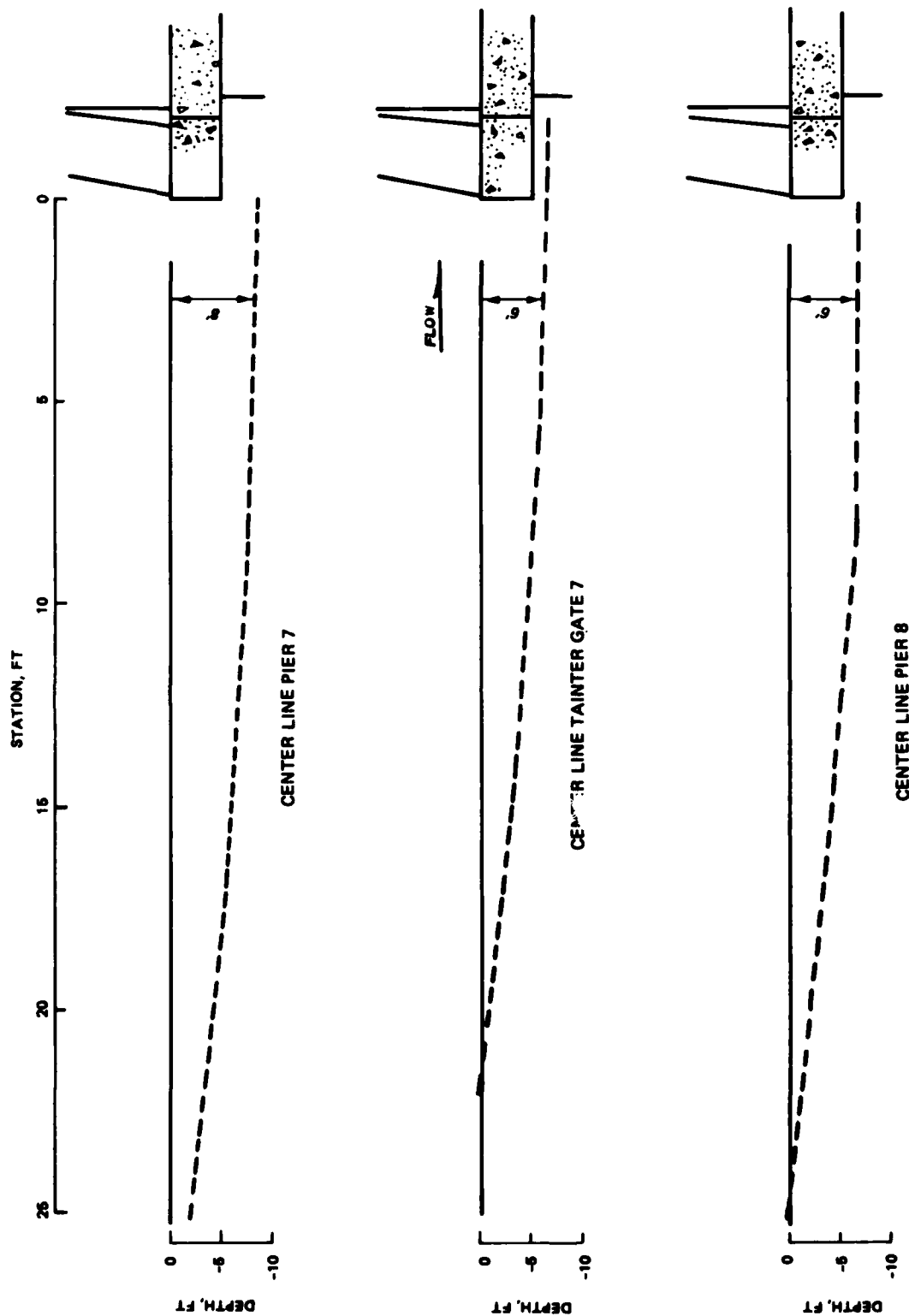
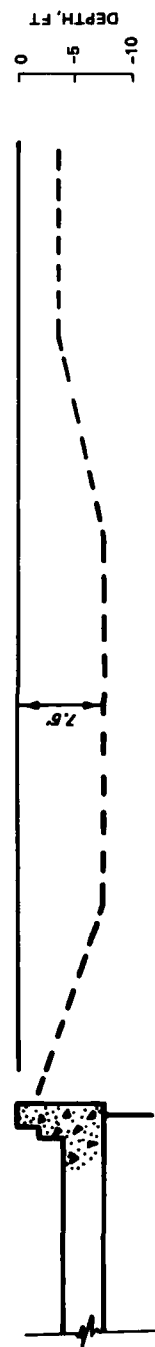
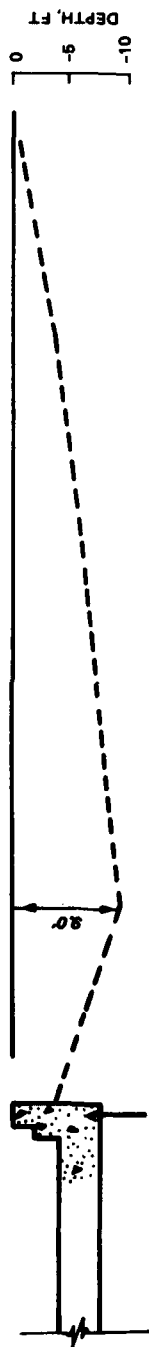
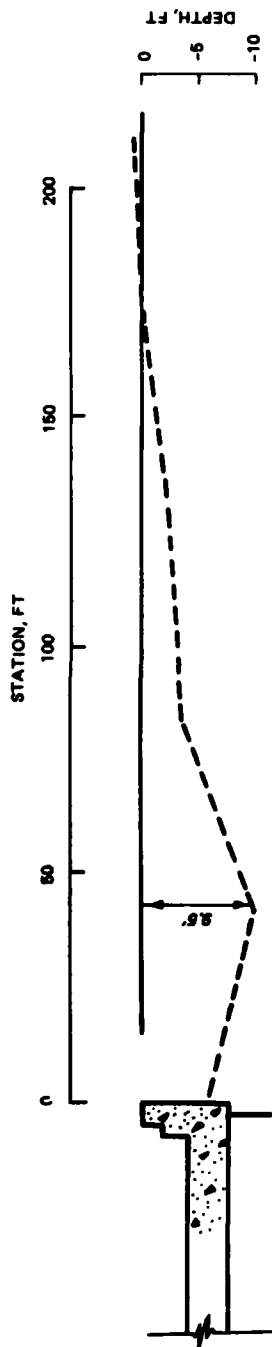


Figure A3. Scour patterns in 1:42-scale model upstream of tainter gate 7 and adjacent piers



TEST CONDITION:
 ONE GATE OPEN FULL
 POOL = 631 (NORMAL) TW = 621 (MINIMUM)
 T = 1 HR (MODEL) = 6.5 HR (PROTOTYPE)

Figure A4. Scour patterns in 1:42-scale model downstream of tainter gate 7 and adjacent piers

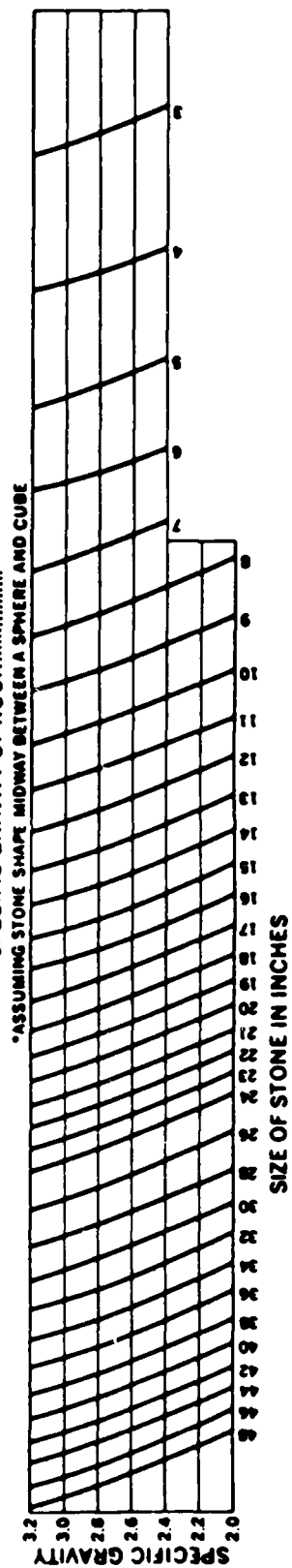
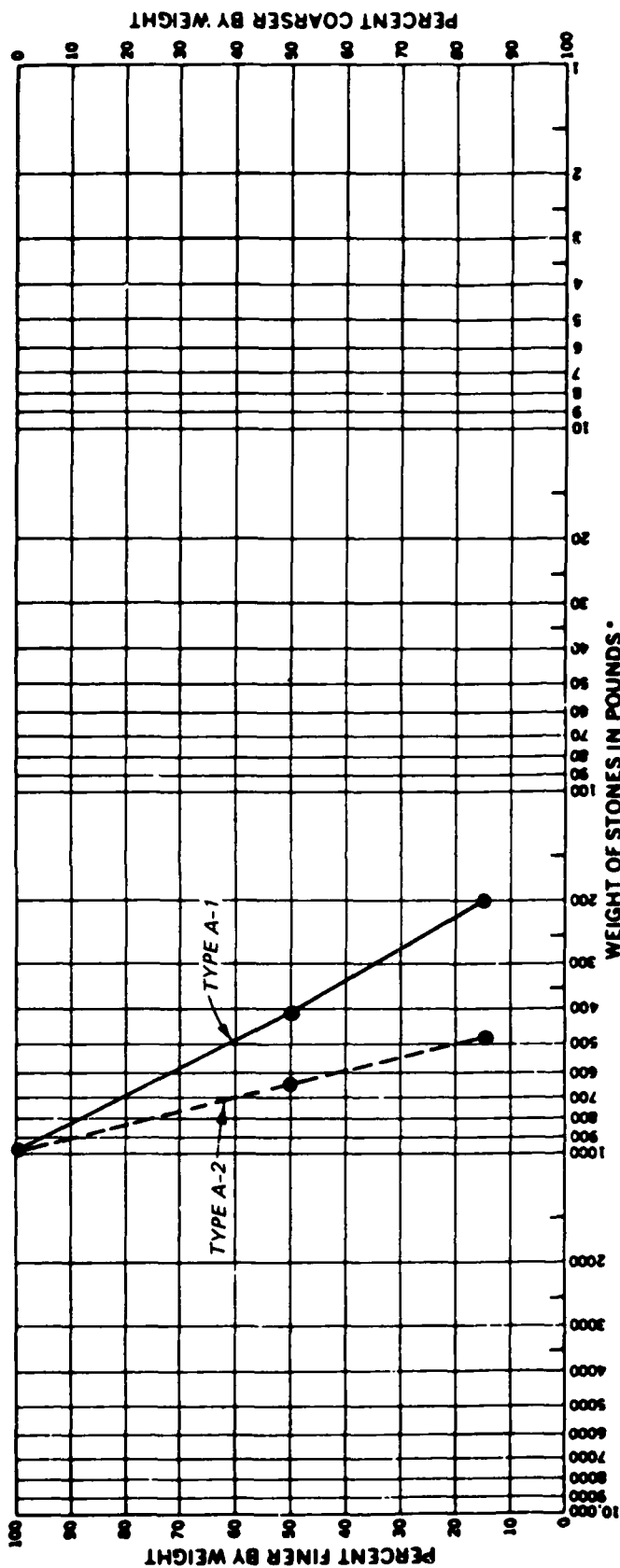


Figure A5. Apron riprap gradation

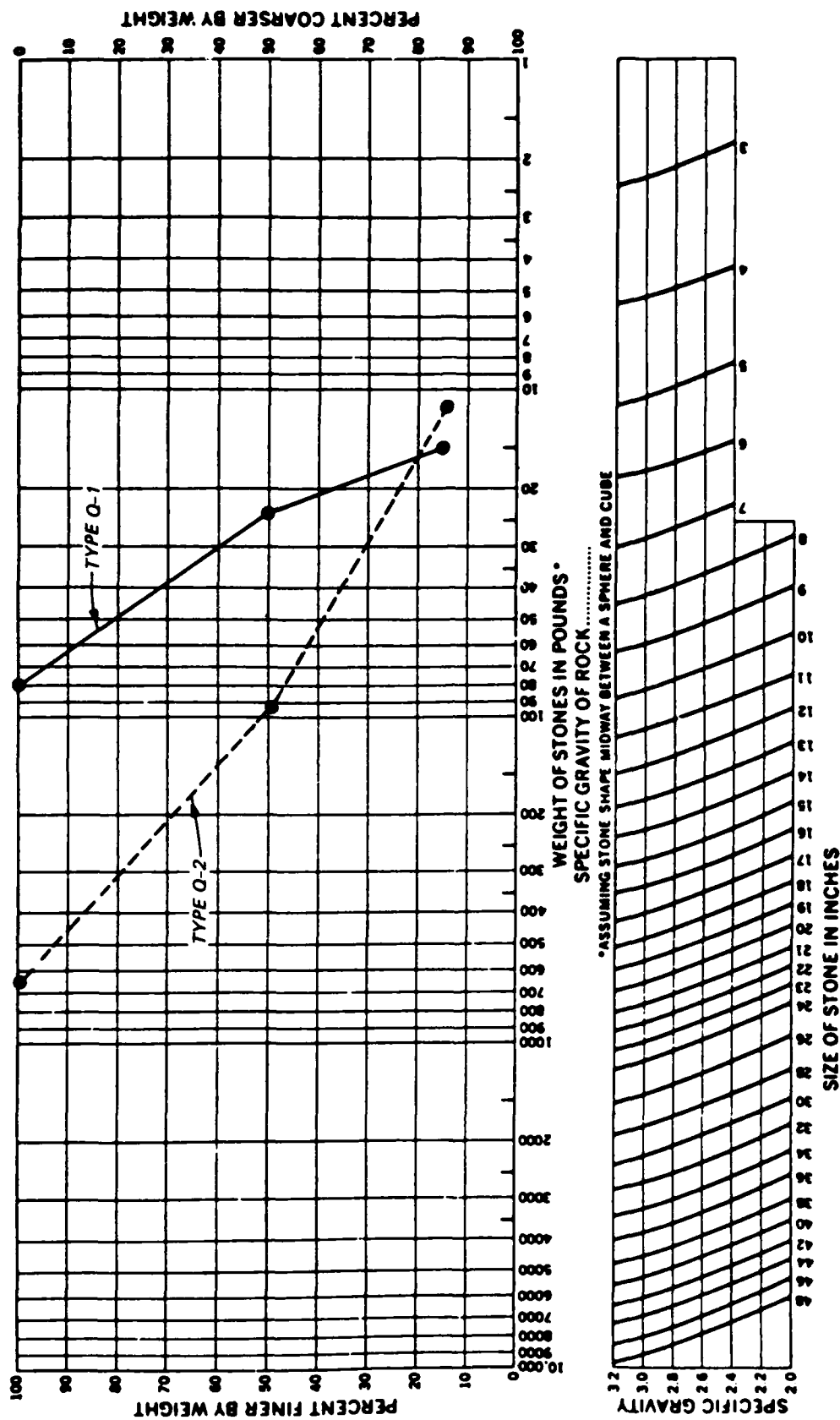


Figure A6. Quarry stone gradation

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